ReNCAT 2.2 User Manual

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1. Getting Started

ReNCAT (the Resilience Node Cluster Analysis Tool) is a software application that suggests portfolios of microgrids and other resilience investments whose locations are selected to reduce the impact of large-scale disruptions to power. This user guide introduces the application, its capabilities, and the underlying concepts.

1.1. Application Overview

When damage to power generation, transmission, or distribution infrastructure prevents the power grid from serving its usual customers, microgrids may partially compensate for the disruption by providing power to small, isolated regions within the service area. Targeted deployment of microgrids may enable some critical services to be made available even before power has been restored to the entire service area. ReNCAT was developed to assess the impact of microgrid investment alternatives on community resilience during infrastructure disruptions, and to identify investment portfolios that have the greatest potential to minimize the negative effects of disruptions at various cost points.

ReNCAT explores potential microgrid locations by examining a simplified representation of the power grid, one that aggregates and approximates loads and conductors. Microgrids are formed within the power network by setting switch states to isolate regions that provide critical services. A portfolio of microgrids improves access to services but requires a monetary investment to install.

ReNCAT can consider other types of investments as well. Investments in power line hardening enable portions of the grid to avoid damage. Investments in grid-independent facilities enable these facilities to provide services regardless of the state of the power network.

Each investment portfolio can be evaluated by its cost, and by the benefit of its investments to the community. The impact an investment portfolio has on community resilience during a power disruption is measured using the Social Burden metric, an approximation of the relative hardship people experience as they work to access critical services like food, shelter, and healthcare. ReNCAT uses a genetic algorithm to explore many candidate investment portfolios, resulting in a set of suggested portfolios with varying tradeoffs between cost and burden mitigation.

1.2. Platform Requirements

ReNCAT runs on computers running Microsoft Windows with .NET Framework version 4.7.2 to 4.8.1 installed. Note that .NET 5 and later are not supported but can be installed concurrently with the required version 4.x of .NET Framework.

1.3. Installation

To install ReNCAT:

- Download ReNCAT from https://www.energy.gov/oe/resilience-modeling-tools
- Extract the files from the downloaded zip file
- Run ReNCAT-setup.exe

2. The ReNCAT User Interface

This section introduces the layout of the ReNCAT application and its usage patterns.

2.1. The ReNCAT Workflow

To use ReNCAT to perform an analysis, follow these general steps:

1. *Create a ReNCAT file.*
   A ReNCAT file is where a project's data is stored, including inputs, settings, and results. A ReNCAT file is a single file stored on your computer's hard drive, much like a Word document or an Excel spreadsheet.
2. *Enter input data.*
   Input data describe the region being studied, including information about the region's power distribution system, its critical infrastructure assets, and its people.
3. *Run an optimization.*
   The optimization applies a genetic algorithm to the input data to identify a set of promising investment portfolios.
4. *Examine results.*
   Optimization results consist of a set of Pareto-optimal investment portfolios identified by the genetic algorithm. ReNCAT makes the details of suggested portfolios available in various results screens. Data can be exported to other tools for further analysis or for visualization purposes.

The list of steps above only includes those tasks that involve the ReNCAT application. An analysis project will include additional pre- and post-processing steps, such as defining the study region, identifying and gathering input data, and communicating insights to stakeholders.

2.2. ReNCAT Files

ReNCAT work is always done in the context of a file. A file includes input data, settings, and optimization results. A file contains everything needed to define, run, and view results for a particular model. ReNCAT files typically have the *rencat* file extension.

You must either create a new file or open an existing file before you can view or modify data in ReNCAT. File management works like most other desktop applications. Using the File menu near the top left corner of the screen, you can create a new file, open an existing file, and save or close the current file.

2.3. Selecting Screens

The ReNCAT user interface consists of a screen selection menu on the left, a screen display area on the right, and a menu and toolbar at the top. Most tasks in ReNCAT are accomplished by viewing or entering data in a particular screen. Each screen allows you to interact with a category of data.

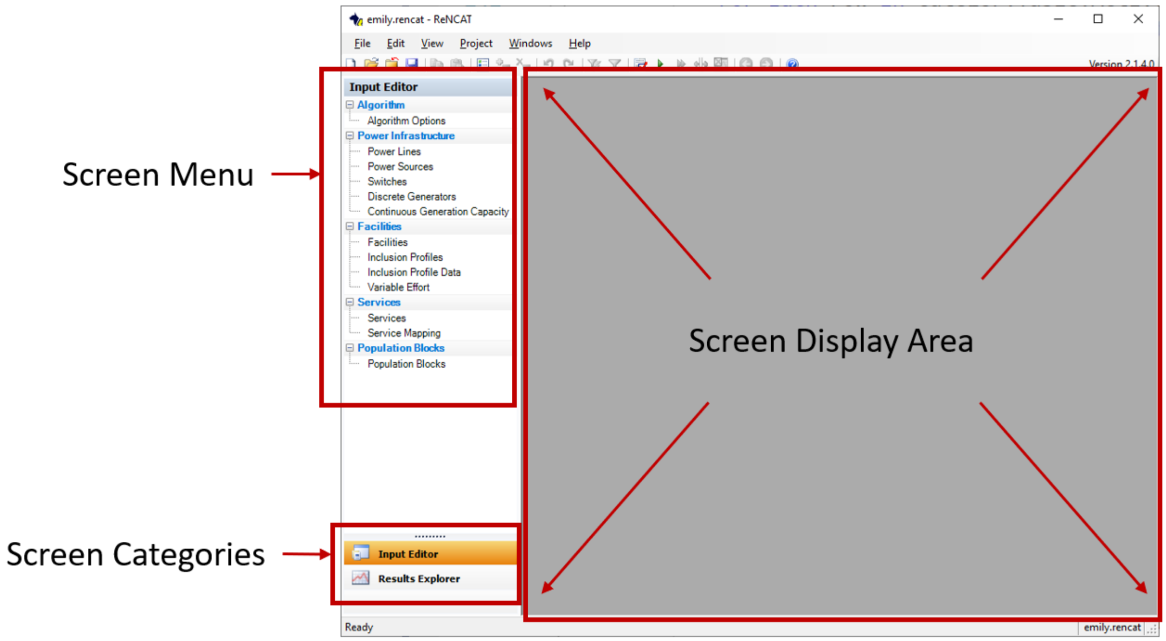

Figure 2-1. User Interface Layout

Clicking on a screen name in the screen menu will display that screen in the display area. For example, clicking on *Power Lines* in the screen menu will display the *Power Lines* screen in the screen display area:

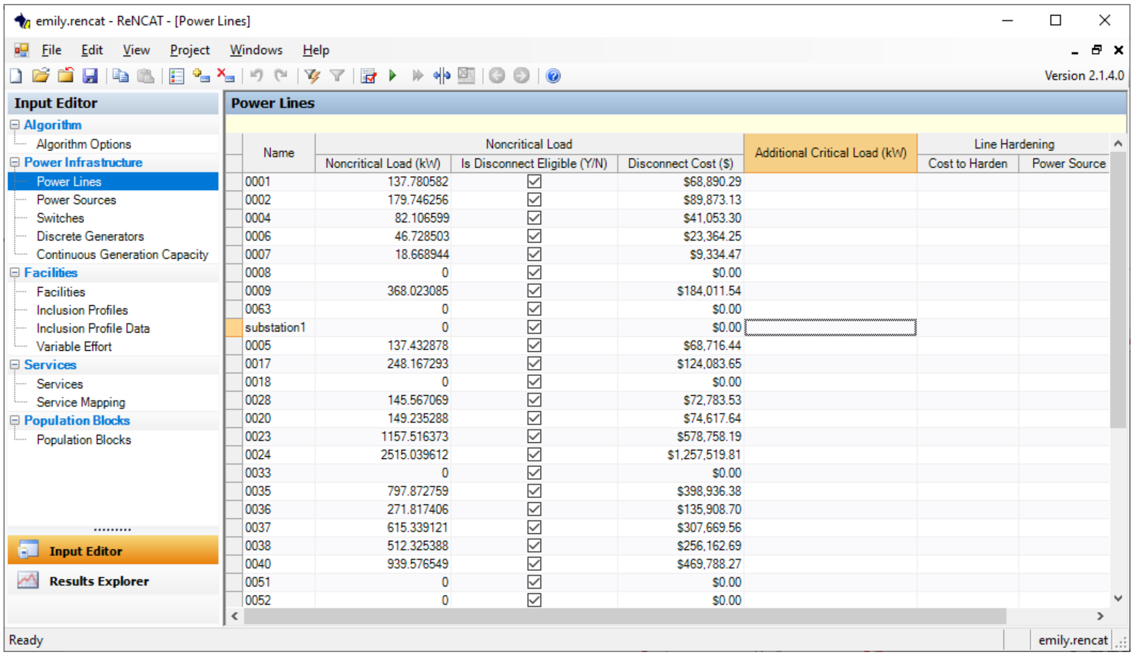

Figure 2-2. User Interface When Displaying an Input Screen

Screens are grouped into two categories, Input and Results, which are listed at the bottom of the screen menu. Clicking on one of the categories will display the names of the screens in that category in the screen menu.

2.4. Working with Tables

Each input screen displays one or more data tables. Most tables are row-based, where each row represents an entity of a particular type. For example, each row in the *Power Lines* screen represents a power line. Headers at the top of the table identify what information should be entered for each row.

To add a new row to a table, right click in or below the table and select *Add New Row* from the pop-up menu that appears. You can also add multiple rows at once by selecting *Add Multiple Rows…* and entering the number of new rows you would like to add.

2.4.1. Multi-Pane Screens

Some screens have more than one table, typically one on the left and one on the right. The table on the left displays categories, while the table on the right shows data related to the selected category. For example, the *Facilities* screen shows a list of facility categories on the left and a list of individual facilities in the selected category on the right. Selecting a different category on the left will change which items are displayed on the right. Adding a new row to the table on the right will automatically assign the new row to the category selected on the left.

Categories are managed by adding and removing rows to the table on the left. However, some views use categories that are managed in another screen. An example is the *Variable Effort* screen, which displays facility categories entered in the *Facilities* screen. When categories are managed in another screen, the *Add New Row* option will be greyed out in the category pane's pop-up menu.

2.4.2. Grid-Based Tables

The *Service Mapping* screen uses a table that is not row-based. Instead, there is a row per facility category and a column per service category. Each cell corresponds to a pairing of one facility category and one service category. Both categories are managed in other screens, so rows and columns cannot be added from the *Service Mapping* screen.

3. Entering Input Data

Model data is entered in the application's input screens. To access input screens, make sure *Input Editor* is selected in the category list at the bottom of the screen menu.

3.1. Power Infrastructure Screens

Power infrastructure screens provide a place to enter information about the power network, its topology, and potential changes to the power network.

3.1.1. Power Lines

The *Power Lines* screen is where information about conductors is entered. There is one line per power line section, where each power line section is a grouping of conductor that is treated as a unit when making decisions during microgrid optimization. It includes the following fields:

Table 3-1. Power Line Fields

Field	Description	Units	Data Type
Name	An identifying name for the power line	–	Text
Non-Critical Load	The total aggregate load imposed on the power line section from all sources other than critical facilities and additional critical loads	kW	Positive floating point
Is Disconnect Eligible	Whether the power line section's non-critical load is allowed to be left unserved	–	Boolean
Disconnect Cost	The cost that is incurred if the line section's non-critical load is left unserved	Dollars	Currency
Additional Critical Load	The total aggregate non-facility load that will be served even if the non-critical load is left unserved	kW	Positive floating point

3.1.1.1. Loads

Note that each power line section has three categories of loads: critical facility loads, additional critical loads, and non-critical loads. Critical facility loads are imposed by facilities entered in the *Facilities* screen. Additional critical loads are loads that will be served even if the power line's disconnect cost is incurred. Non-critical loads are loads that will not be served if they are disconnected, i.e., if the power line's disconnect cost is incurred.

3.1.2. Power Sources

The *Power Sources* screen is used to represent existing generators and other existing sources of power generation capacity. Each power source is associated with a single power line. That power line will have access to the power source's generation capabilities regardless of decisions made during microgrid optimization. The region served by a power source expands beyond its associated line as power flows through closed switches.

Table 3-2. Power Source Fields

Field	Description	Units	Data Type
Name	An identifying name for the power source		Text
Generation Capacity	The maximum load that can be served by this power source	kW	Positive floating point
Power Line	The power line associated with this power source	Power Line Name	

3.1.3. Switches

The *Switches* screen represents potential connection points between two power line sections. Switches can be open or closed. If a switch is closed, its two power line sections are connected at that point and power can flow between the two power line sections. If a switch is open, the two power line sections are not attached at that point. Switches in ReNCAT may be switches that currently exist in the distribution system, or they may be proposed switches that will incur an installation cost if selected by the optimization.

Switches serve as potential microgrid boundaries. If a power line is part of a microgrid, then any power line attached to it by a closed switch is also part of the same microgrid. Two lines separated by an open switch are not part of the same microgrid, unless there is another path through closed switches that enables power to flow between the two power line sections.

The state of each switch is selected during the microgrid placement optimization. Switch states are among the key decisions made by the optimization algorithm to determine microgrid locations and boundaries.

Each switch has two associated costs, a cost when closed and a cost when open. In each investment portfolio, one of these two costs will be incurred depending on the selected switch state in that portfolio. Appropriate values for the two costs depend on what the switch represents. The following are examples of associated switch costs for different configurations and scenarios.

- Manual switches may incur a cost to upgrade to automatic switches if their selected switch state is the opposite of their normal state (i.e., ReNCAT chooses to open a normally closed switch)
- If manual switches are not upgraded, they incur a cost to change the state of the switch
- If a switch represents a new switch location, there is an associated cost to open that represents the installation cost. Leaving the switch closed represents not installing a new switch at that location and does not incur a cost.

Table 3-3. Switch Fields

Field	Description	Units	Data Type
Name	An identifying name for the switch		Text
Power Line 1	One of the two power lines that are connected if the switch is closed		Drop-down selection
Power Line 2	The second power line that is connected if the switch is closed		Drop-down selection
Cost When Closed	The cost incurred if the switch is closed	Dollars	Currency
Cost When Open	The cost incurred if the switch is open	Dollars	Currency

3.1.4. Discrete Generators

The *Discrete Generators* screen is where information is entered for new generators that can be purchased. New generators are purchased to supply power to microgrids when existing power sources do not have sufficient generation capacity or can't be reached through closed switches. PV systems can be included by specifying the smallest kW unit of PV to be considered. If PV is chosen as the generation option, ReNCAT will purchase multiple "units" to cover the generation needs.

Table 3-4. Discrete Generator Fields

Field	Description	Units	Data Type
Name	An identifying name for the generator		Text
Capacity	The maximum load this generator can support	kW	Positive floating point
Cost	A cost incurred for each generator of this type that is purchased	Dollars	Currency

3.2. Facility Screens

Facility screens provide a place to enter information about facilities that should be considered during a microgrid placement optimization. Facility data describe service-providing locations of interest, their relationship to the power network, and the effort community members must expend to access each facility's services.

3.2.1. Facilities

The *Facilities* screen is where you enter information about critical infrastructure locations that provide services when they have power. Each facility is assigned to a category (such as a gas station). Some of the facility's properties are determined by its category, such as the services it provides. Other properties are specific to the individual facility, such as its location and what power line it is attached to.

The *Facilities* screen has two panes, the Category pane on the left, and the Facility pane on the right. The Category pane on the left is where you add and remove facility categories. The Facility pane on the right is where you add and remove individual facilities within a category. Clicking on a category on the left will display facilities in that category on the right.

The Category pane on the left has the following fields:

Table 3-5. Facility Category Fields (Left Pane)

Field	Description	Units	Data Type
Name	The name of the facility category		Text

The Facilities pane on the right has the following fields:

Table 3-6. Facility Fields (Right Pane)

Field	Description	Units	Data Type
Name	The name of the facility		Text
Power Line	The power line section this facility gets its power from	Power Line Name	
Latitude	The latitude of the facility's location	Degrees Latitude	Floating point
Longitude	The longitude of the facility's location	Degrees Longitude	
Is Disconnect Eligible	Whether the facility is allowed to be left without power, even when its associated power line is part of a microgrid		Boolean
Disconnect Cost	The cost incurred if the facility is left without power when its associated power line is part of a microgrid	Dollars	Currency
Load	The load imposed by this facility on its associated power line	kW	Positive floating point
Zero Distance Effort	The effort to acquire this facility's services, before considering distance	Effort units	Positive floating point
Effort Per Foot	The additional effort to acquire this facility's services for each foot of distance from the facility's location	Effort units	Positive floating point

3.2.1.1. Disconnected Facilities

Each facility is associated with a power line. If the facility's power line is part of a microgrid then the facility's load is included in the total load supported by the microgrid. The microgrid must have enough generation capacity to support its total load; new generation capacity must be purchased if existing power sources are not sufficient to support the total load.

If a facility is flagged as being disconnect-eligible then the microgrid optimization may choose to leave the facility without power even if the facility's power line is in a powered microgrid. This reduces the microgrid's total load, which in turn may reduce the size or number of new generators that must be purchased. Disconnecting a facility from its power line incurs a cost, specified in the Disconnect Cost field. The microgrid optimization algorithm will only consider disconnecting a facility if doing so reduces the cost of purchasing generators by more than the facility disconnect cost. Also note that a facility may only be disconnected if its power line is part of a microgrid – disconnecting a facility from an unpowered power line provides no benefit.

3.2.1.2. Effort

Effort parameters represent the time, financial impact, and other hardship one experiences when accessing a facility's services. Effort is a major element of the Social Burden metric. The zero-distance effort represents effort required regardless of your location relative to the facility, such as time spent shopping or waiting in line. The per-foot effort represents effort that increases with distance, such as travel, or possibly a reduction in service effectiveness due to distance.

3.2.2. Non-Grid Facilities

Non-grid facilities are critical infrastructure locations that provide services without requiring a connection to the power grid. Instead of requiring power from the grid, non-grid facilities require the payment of an activation cost before they can provide their services. Like other facilities, each non-grid facility is assigned to a category that determines some its properties, such as the services it provides. Other properties are specific to the individual facility, such as its location and activation cost.

It generally requires effort to access the services of a non-grid facility, just as it does for other facilities. See Section 3.2.1.2: *Effort* above for a discussion of effort and effort parameters.

The *Non-Grid Facilities* screen has two panes, the Category pane on the left, and the Facility pane on the right. The Category pane on the left is where you add and remove non-grid facility categories. The Facility pane on the right is where you add and remove individual non-grid facilities within a category. Clicking on a category on the left will display non-grid facilities in that category on the right.

The Category pane on the left has the following fields:

Table 3-7. Non-Grid Facility Category Fields (Left Pane)

Field	Description	Units	Data Type
Name	The name of the non-grid facility category		Text

The Facilities pane on the right has the following fields:

Table 3-8. Non-Grid Facility Fields (Right Pane)

Field	Description	Units	Data Type
Name	The name of the non-grid facility		Text
Latitude	The latitude of the facility's location	Degrees Latitude	Floating point
Longitude	The longitude of the facility's location	Degrees Longitude	
Activation Cost	The cost incurred to enable the non-grid facility to function and provide its services	Dollars	Currency
Zero Distance Effort	The effort to acquire this facility's services, before considering distance	Effort units	Positive floating point

Effort Per Foot	The additional effort to acquire this facility's services for each foot of distance from the facility's location	Effort units	Positive floating point

3.2.3. Variable Effort

Normally the effort required to acquire services from a given facility only changes with distance to the facility. However, for some facility categories the effort may also depend on the number of operational facilities of that type. For example, the time required to get gas may increase if there are only a few operational gas stations with long lines of waiting vehicles.

The *Variable Effort* screen allows effort parameters to depend on the number of operational facilities of a given category. The screen has two panes, the Facility Category pane on the left and the Variable Effort pane on the right.

The pane on the left displays a list of facility categories, including both grid-dependent facility categories and non-grid facility categories:

Table 3-9. Variable Effort Category Fields (Left Pane)

Field	Description	Units	Data Type
Name (Read-Only)	The name of the facility category		Text

Clicking on a facility category on the left causes the variable effort parameters for that category to be displayed in the right pane:

Table 3-10. Variable Effort Fields

Field	Description	Units	Data Type
Count	The maximum number of operational facilities that will cause this row's parameter values to be used	Number of facilities	Positive Integer
Zero Distance Effort	The zero-distance effort for each facility of this category, when the number of operational facilities of this category is no greater than the row's Count	Effort Units	Positive floating point
Effort Per Foot	The additional effort for each foot of distance from the facility, when the number of operational facilities of this category is no greater than the row's Count	Effort Units	Positive floating point

Any facility whose category has at least one row in the *Variable Effort* screen may take its effort parameters from the data entered here instead of using the effort parameters specified in the *Facilities* screen. Which Variable Effort row to use is determined by comparing each row's Count with the number of operational facilities of the relevant facility category. The Count is an upper bound on the number of operational facilities for the row to apply; it can be read as *Up To*. The effort parameters used during Social Burden metric assessment will be taken from the row with the smallest count that is not less than the number of operational facilities. If there is no row whose Count is equal to or greater than the number of operational facilities of the relevant category, then effort parameters are taken from the *Facilities* screen.

For example, consider a model with 3 variable effort rows for gas stations, one row with a Count of 2, one with a Count of 4, and one with a Count of 7. An investment portfolio that provides power to 4 gas stations would use the data from the row whose Count is 4, while a portfolio with 5 gas stations would use the row with a Count of 7, and a portfolio with 8 gas stations would use the per-facility effort parameters entered in the *Facilities* screen.

3.3. Services

Services represent categories of human need that will be considered by the microgrid placement optimization. Service screens are used to identify service categories, and to describe facilities' ability to provide services.

3.3.1. Services

The *Services* screen is where categories of need are identified:

Table 3-11. Service Category Fields

Field	Description	Units	Data Type
Name	An identifying name for the service category		Text
Weight	The relative importance of this service category	Unitless	Positive floating point

The weight is used to scale a service category's contribution to total burden values. If a weight is not provided, the weight is automatically set to 1.

3.3.2. Service Mapping

The *Service Mapping* screen is used to specify which services each facility category provides, and at what level.

The service mapping has one row per facility category (including both grid-dependent and non-grid facility categories), and one column per service category. Each cell indicates the degree to which the row's facility category can provide the column's service. Larger numbers indicate a greater ability to supply the service. Service levels scale linearly – doubling a service level doubles the burden reduction from each facility of that type.

Each cell in the service mapping has the following fields:

Table 3-12. Service Mapping Fields

Field	Description	Units	Data Type
Facility Category (Read-Only)	From the cell's row. The type of facility this cell's value applies to.		Text
Service Category (Read-Only)	From the cell's column. The type of service this cell's value applies to.		Text
Service Level	The degree to which each facility of this facility category provides access to this service.		Positive Floating Point

Empty cells are equivalent to entering a zero, meaning facilities in this category do not provide the indicated service.

3.4. Population Blocks

The study area is divided into population blocks, where each block represents the people who live in a particular region within the study area. They often correspond to census block groups, though other levels of granularity may be used as well.

3.4.1. Population Blocks

The *Population Blocks* screen is where information about the people in the study region is entered. It has the following fields:

Table 3-13. Population Block Fields

Field	Description	Units	Data Type
Name	An identifying name for this group of people		Text
Latitude	The latitude of the centroid of this block's location	Degrees Latitude	Floating point
Longitude	The longitude of the centroid of this block's location	Degrees Longitude	Floating point
Attainment Factor	The relative ability of this group of people to absorb increases in hardship to acquire services		Floating point
Population	The number of people in the block	People	Integer

3.4.1.1. How Block Coordinates Affect Social Burden

Population blocks convey how people are distributed throughout the study area. Block centroids are used to calculate the distance between the people in the block and facilities. Distances to facilities, combined with each facility's *Effort Per Foot* parameter, is a major element of the Social Burden calculation.

3.4.1.2. Attainment Factors

To account for differences in people's relative ability to absorb additional travel, cost, and disruption as they acquire services, analysts must assign a numeric attainment factor to each population block. Population blocks with a lower attainment factor experience a greater increase in Social Burden when critical services become harder to obtain. Median household income is often used as the attainment factor. Other quantitative metrics can be used instead, provided they estimate the distribution of different people's abilities to absorb additional travel, cost, and disruption.

A block's contribution to overall Social Burden is scaled by the inverse of its attainment factor. Doubling a block's attainment factor cuts its contribution to overall Social Burden in half.

3.5. Threats

A threat is a scenario that may make certain facilities and power lines unavailable regardless of microgrid locations. For example, a flood may put certain parts of the study region under water. A threat profile is used to flag certain facilities and power lines as ineligible to receive power. Multiple threat profiles can be stored in a single ReNCAT file, each with its own set of ineligible facilities and power lines. Each optimization run will apply one or more threat profiles.

3.5.1. Threat Profiles

The *Threat Profiles* screen allows you to add or remove threat profiles from the file and indicate how the threat will be incorporated into optimization runs.

Table 3-14. Threat Profile Fields

Field	Description	Units	Data Type
Name	The name of the threat profile		Text
Include in Optimization	Whether this threat should be considered during an optimization run		Boolean
Optimization Weight	The relative importance of this threat profile compared to other threat profiles included in the same optimization run		Floating Point

3.5.1.1. Design Basis Threats

The effectiveness of an investment portfolio changes from one threat scenario to another. For example, an investment portfolio that hardens power lines in a specific region may be very effective against threats that damage power lines in that region, but ineffective against a threat that damages another part of town.

An investment portfolio optimization seeks to identify the set of microgrids and other investments that best address one or more threat scenarios. The threats used to evaluate investment portfolios during optimization are called *design basis threats*. A threat profile is marked as a design basis threat by selecting its Include in Optimization checkbox in the *Threat Profiles* screen. Every optimization must include at least one design basis threat. There can be multiple design basis threats, although adding more design basis threats increases the time to solve the optimization.

3.5.2. Facility Damage

This screen indicates which facilities are affected by each threat profile.

The left pane has a list of facility categories, including both grid-dependent categories and non-grid categories, as defined in the *Facilities* and *Non-Grid Facilities* screens:

Table 3-15. Facility Category Fields (Left Pane)

Field	Description	Units	Data Type
Name (Read-Only)	The name of the facility category		Text

The right pane displays a row for each facility in the selected category. Selecting a facility category in the left pane changes which facilities are displayed in the right pane. In addition to the column with facility names, the right pane has one column per threat profile:

Table 3-16. Threat Profile Facility Damage Fields

Field	Description	Units	Data Type
Facility Name	The name of the row's facility		Text

(Read-Only)			
<Facility Inclusion Profile>	One column per threat profile, as defined in the Threat Profiles screen. The column header is the name of the threat profile. Tick a checkbox to indicates the row's facility is ineligible to function in the column's threat profile.		Boolean

Each facility has a checkbox per threat profile. If the checkbox is checked then the facility is impacted by the threat and is not allowed to operate under this threat, regardless of any investments made. If the checkbox is not checked then the facility is eligible to operate, provided the required investments have been made. By default, all facilities are eligible to operate when a new threat profile is created.

3.5.3. Power Line Damage

This screen allows you to indicate which power lines are affected by each threat profile.

Table 3-17. Facility Inclusion Fields

Field	Description	Units	Data Type
PowerLine (Read-Only)	The name of the row's power line		Text
Cost to Harden (Optional)	The cost incurred to harden the power line		
Power Source When Hardened (Optional)	An existing power source that the line will receive power from if (and only if) the line is hardened.		
<Threat Profile>	One column per threat profile, as defined in the Threat Profiles screen. Column header is the name of the threat profile. Checkbox indicates whether the power line must be hardened to be eligible to receive power in the column's threat profile.		Boolean

Each power line has a checkbox per threat profile. If the checkbox is checked then the power line is impacted by the threat and is not allowed to receive power under this threat unless the line is hardened.

The optimization algorithm chooses which lines to harden in each investment portfolio. Hardening a line incurs the line's hardening cost, as specified in the line's Cost to Harden field. Lines without a value entered in the Cost to Harden field are not eligible to be hardened.

Hardening a power line has two potential impacts. First, hardening a line negates the effects imposed by threat profiles on the line. Hardened lines can carry power and can be included in powered microgrids, even under threat profiles that would otherwise damage the line and make it ineligible to carry power.

Second, hardening a power line attaches the line directly to an existing power source, if the line's Power Source When Hardened field is not left blank. If the line hardening cost is incurred and a Power Source When Hardened has been specified, the hardened line will carry power and will draw its power from the specified existing power source. Power lines that are modeled in this manner are sometimes referred to as express feeders.

4. Investment Portfolio Optimization

ReNCAT uses the information entered in the input screens to identify beneficial locations for microgrid placement and to select other beneficial investments. ReNCAT uses a genetic algorithm (GA) to explore candidate investment portfolios. The sections below describe how to configure and launch an optimization and discuss optimization algorithm details.

4.1. Overview of the Optimization Algorithm

It is not necessary to understand the details of the optimization algorithm to use ReNCAT. However, some familiarity with the algorithm's approach will allow you to select configuration options that fit your model well.

The ReNCAT optimization algorithm is a genetic algorithm, a nature-inspired search algorithm that evaluates a large number of investment portfolio designs, using what it learns from prior evaluations to guide selection of additional designs to assess. The algorithm evaluates portfolio designs in large batches called generations. In the first generation the designs are random—portfolios consist of randomly placed microgrids and randomly selected additional investments. In all subsequent generations, the new designs are variations and combinations of previous generations' designs, with the best designs encountered so far having greater influence on new designs.

The algorithm maintains a list of the best designs it has encountered so far, called the *design population*. After a generation's designs have been evaluated, each design is either introduced into the population or discarded, depending on how well it compares to the designs already in the population.

Before proceeding to the next generation, the algorithm checks whether any stopping criteria have been satisfied. Examples of stopping criteria include the number of generations, the total number of evaluated designs, total time, and insufficient change in the population.

4.2. Optimization Configuration Options

Certain elements of the optimization algorithm can be controlled by configuration options. These options are set in the *Algorithm Options* screen found in the *Input Editor* section of the screen menu.

Table 4-1. Configuration Option Fields

Field	Description	Units	Data Type
Random Seed	A number which influences the algorithm's random decisions		Positive Integer
Population Size	The number of investment portfolios the genetic algorithm maintains in its design population	Portfolios	Positive Integer
Evaluation Concurrency	The number of candidate investment portfolios to assess simultaneously, subject to the number of threads available on the computer	Threads	Floating Point
Linear Solver	The linear solver used during the optimization process		Drop-Down Selection

Max Generations	The maximum number of generations before the genetic algorithm automatically stops	Generations	Positive integer
Max Evaluations	The maximum number of investment portfolios to evaluate across all generations before the genetic algorithm automatically stops	Portfolios	Positive integer
Max Time	The maximum wall clock time before the genetic algorithm automatically stops	Seconds	Positive integer
Change Tracking: Fraction Change	The fraction of investment portfolios in the algorithm's population that must change between generations to prevent the algorithm from stopping	Fraction (0 to 1)	Floating point
Change Tracking: Tracked Generations	The number of consecutive generations that must stay below the Fraction Change to trigger the algorithm to stop	Generations	Positive integer
Log Filename	The full path to a file to write log information into, leave blank to disable logging to a file	File path	Text
Logging Level	The amount of information to log to the log file		Drop-down selection
Print Each Population	Whether to write a file with the contents of the population at the end of each generation		Boolean
Print Final Population	Whether to write a file with the contents of the population at the end of the optimization		Boolean

4.2.1. Choosing a Population Size

The size of the population strongly influences the quality of results and the speed of the algorithm. A larger population increases the time required for each generation but may improve results in some cases. A larger population also uses more computer memory. Smaller populations run more quickly for each generation but may fail to make progress in a timely manner. If a run's results do not seem to have adequately explored the search space, increase the population size and run the optimization again. We recommend population sizes between 200 and 2,500.

4.2.2. Change Tracking Convergence

One stopping criterion is to stop if the algorithm has not made sufficient improvement in recent generations. It is controlled with two options: Fraction Change and Tracked Generations. The Fraction Changed is a value between 0 and 1 that indicates how much the population must change to prevent the algorithm from stopping. The Tracked Generations is the number of generations that must fail to make progress before the algorithm will stop. For example, if Fraction Change = 0.3 and Tracked Generation = 10, then the algorithm will stop if less than 30% of the current population was introduced in the last 10 generations. Stated another way, the algorithm will stop if at least 70% of the population's designs were introduced at least 10 generations ago.

4.3. Running an Optimization

After all model input has been entered and optimization configuration options have been set, you can run an optimization by selecting *Run Optimization* from the *Project* menu, or by clicking the green arrow on the toolbar.

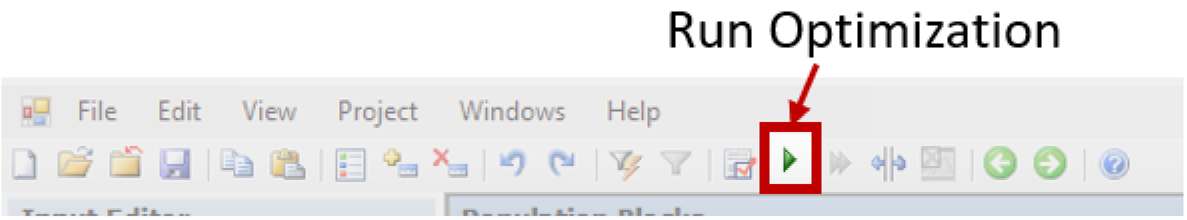

Figure 4-1. Location of *Run Optimization* Button

This will first cause the model input to be validated. If no errors are found in the input, the optimization begins. During the optimization process, a window showing optimization status is displayed. This window shows statistics about the optimization and its progress.

The optimization progresses in generations. During each generation, many candidate investment portfolios are evaluated. Because evaluation takes a non-trivial amount of time, there is often a delay of several minutes between each generation. Statistics are updated after each generation is evaluated.

The Optimization Status window has an *Interrupt* button. Clicking this button will cause the optimization to end after the current generation is fully evaluated. After the generation's evaluation is complete, a notification is displayed indicating the optimization completed successfully. Because of the time it takes to evaluate a generation's portfolios, there may be a delay of several minutes after clicking the Interrupt button before this notification is displayed.

Because the optimization is based on a genetic algorithm, it tends to produce better results if it is allowed to run longer. Each generation of evaluations provides information that the genetic algorithm uses to predict how to improve investment portfolios it has already explored. When the algorithm stops, either because it was interrupted or because it satisfied one of the stopping criteria, the results are the best portfolios it has found so far, which are not necessarily the best portfolios possible. This is why an interrupted optimization is considered successful, even though it was terminated early.

4.4. Investment Portfolio Evaluation

ReNCAT generates and evaluates many investment portfolios during the optimization process. Each portfolio is evaluated in a two-step process. First, a set of heuristics is applied to ensure the portfolio conforms to design rules. Second, the portfolio's cost and Social Burden metrics are calculated.

4.4.1. Portfolio Design Rules

In its most basic form, an investment portfolio design consists of switch states, facility power states, line hardening investments, and non-grid facility investments. To convert this basic design into a more complete portfolio definition, additional decisions must be made regarding load shedding, generator purchases, and threat-specific configuration options.

When optimizing against multiple design threats, some decisions are made once and apply to all threats. Other decisions are made once per threat. Shared decisions include all investments, switch states, and microgrid boundaries. All decisions that incur a cost are shared decisions. On the other hand, per-threat decisions reflect how to configure the system to best address the specific threat while honoring shared decisions. Per-threat decisions include whether to power each microgrid, and which facilities and loads to disconnect. A per-threat configuration indicates which facilities are operational in the context of the threat, given the set of shared investments.

All decisions honor a set of design rules:

- Any facility that was damaged by the active threat may not receive power.
- Any power line that was damaged by the active design basis threat may not carry power unless it is hardened.
- Any power line that is attached to an existing power source is considered powered, unless it was damaged by the active threat and not hardened.
- Any powered facility must be connected to a line with power. Another way of stating this requirement is that any line that supports at least one powered facility must also be powered.
- Any powered line is, by definition, part of a microgrid. Starting from any powered line, all other power lines that can be reached by traversing closed switches are also part of the same microgrid.
- All lines that are not part of a microgrid are unable to carry power.
- Any unpowered facility that is attached to a powered line must be disconnected from its line. If the unpowered facility is not eligible to be disconnected from its line, the entire microgrid must be left without power. The optimization will generally avoid forming microgrids that are left unpowered, except under some multi-threat configurations described below.
- Each microgrid must have enough generation capacity to support all its non-disconnected loads. If existing generation capacity is not sufficient, a combination of the following actions can be used to bring the microgrid into compliance:
    - Purchase one or more discrete generators
    - Disconnect one or more non-critical loads from the microgrid's power lines
    - Disconnect one or more of the microgrid's facilities, leaving the facility without power

  Each of these actions has an associated cost. ReNCAT will always choose the set of actions with the lowest combined cost.

When more than one design basis threat is included in the optimization, the system configuration may differ between threats in the following ways:

- A grid-dependent facility may be disconnected under some threats but not others. This can happen if the facility is damaged under some threats but not others. Disconnecting a damaged facility enables its associated power line to be part of a powered microgrid even though the damaged facility is ineligible to receive power. Facility disconnection costs are incurred if the facility is disconnected under at least one threat.
- A non-grid facility whose activation cost was paid will be disabled in threats that damage the facility, but operational in threats that do not damage the facility.

- A non-critical load may be disconnected under some threats but not others. This is a side effect of conditionally disconnected facilities. A line's non-critical disconnect cost is incurred if the non-critical load is disconnected under at least one threat.
- A microgrid may be powered under some threats but not others. The optimization may choose to form a microgrid that supports valuable facilities under some threats even if it is unable to operate under other threats. This can occur if an unhardened line in the microgrid is damaged under some threats but not others, or if any facility that cannot be disconnected is damaged under some threats but not others. It can also occur if <u>all</u> facilities in a microgrid are damaged in some threats but not others, making it cheaper to de-power the microgrid instead of paying all facility disconnect costs.

Note that the same set of investments and switch states applies to all threat profiles, even when some investments do not apply to all threats. The portfolio's investments are assumed to have been made *before* the threat is realized, so their costs are incurred regardless of whether they are leveraged in all design basis threats. If an investment is chosen for any threat scenario, its cost is incurred in all scenarios.

4.4.2. Objective Calculations

The quality of each investment portfolio is determined by two metrics: cost and Social Burden.

4.4.2.1. Cost Calculation

As discussed in the previous section, a complete portfolio design consists of more than microgrid locations. It also includes decisions regarding facilities that have been disconnected from their power lines, disconnected non-critical loads, purchase of generation capacity, line hardening investments, and non-grid facility activations. Many of the elements of an investment portfolio design have a cost associated with them:

- *Switch state costs* – Each switch has a cost for its open state and a cost for its closed state. Each switch incurs the cost corresponding to its selected state.
- *Generator purchase costs* – Any discrete generators or PV capacity acquired to power microgrids incur the associated purchase cost.
- *Non-facility load disconnection costs* – Disconnecting non-critical loads from a power line incurs the cost entered in the Power Lines screen. Disconnect costs are only incurred for power lines that are part of a microgrid, and only if ReNCAT chooses to disconnect the non-critical load. ReNCAT will only choose to disconnect non-critical loads if doing so is less expensive than purchasing additional generation capacity.
- *Facility disconnection costs* – Disconnecting a facility's load from a power line incurs the disconnect cost entered in the Facilities screen. Disconnect costs are only incurred if the facility's power line is part of a microgrid, and only if ReNCAT choses to disconnect the facility's load. ReNCAT will only choose to disconnect facility loads if doing so is less expensive than purchasing additional generation capacity. A disconnected facility is left without power, unable to provide its services.
- *Non-grid facility activation costs* – Enabling a non-grid facility to provide its services incurs the facility's activation cost entered in the *Non-Grid Facilities* screen.

- *Line hardening costs* – Hardening a line incurs its line hardening cost entered on the Threat Line Damage screen. A line will only be hardened if it is the lowest cost method to provide power to

The total cost for a portfolio is the sum of the cost elements listed above. When optimizing against multiple design basis threats, any cost incurred in at least one threat configuration is included in the cost calculation. Costs that are incurred by multiple threats are only counted once.

4.4.2.2. Social Burden Calculation

The Social Burden value will vary from one portfolio to the next depending on which service-providing facilities are operational. A grid-dependent facility is operational if its associated power line is part of a microgrid, and the facility has not been disconnected. All other grid-dependent facilities are left without power. A non-grid facility is operational if its activation cost has been incurred and it was not damaged by the current threat.

When comparing two portfolios, each with its own set of operational facilities, several factors may contribute to one portfolio having a lower Social Burden than the other. Social Burden is lowered when additional facilities are brought online; when the geographic distribution of powered facilities aligns with the distribution of people within the study area; when a balance of service categories is supported; and when facilities that provide greater levels of service are preferred over smaller facilities that provide a lower level of service.

When there is more than one design basis threat, the total Social Burden value is the weighted sum of the Social Burden metric for each individual threat, where the weight is entered into the *Threat Profiles* screen in the Optimization Weight field.

The Social Burden metric is described in greater detail in "*Measuring Social Infrastructure Service Burden*", available at https://energy.sandia.gov/wp-content/uploads/2022/12/Social-Infrastructure-Burden-White-Paper_Final.pdf.

4.5. Optimization Results

The ReNCAT optimization seeks to minimize both cost and Social Burden. Both objectives are minimized simultaneously by a multi-objective algorithm that uses Pareto optimality to assess fitness. The results of an optimization consist of the Pareto-optimal investment portfolios discovered during optimization. A portfolio is Pareto-optimal only if every alternative with a lower cost also has a higher burden, and every alternative with a lower burden has a higher cost. Pareto optimality is only based on portfolios evaluated during optimization; there may be portfolios which were not discovered by the optimization algorithm that are better than the reported Pareto set.

5. Viewing Results

After an optimization has completed successfully, results are seen in the results screens. Click on *Results Explorer* at the bottom of the screen menu to display the available results screens.

5.1. Pareto

The *Pareto* screen displays a chart with the best investment portfolios discovered during optimization, where "best" is defined as Pareto-optimal for cost and burden, as described in Section 4.5: *Optimization Results* above. Each dot in the Pareto chart represents a full portfolio consisting of one or more microgrids and a corresponding set of investments. Hovering over a dot displays core information about the portfolio. Sliders at the bottom of the Pareto screen allow portfolios to be filtered based on cost or burden.

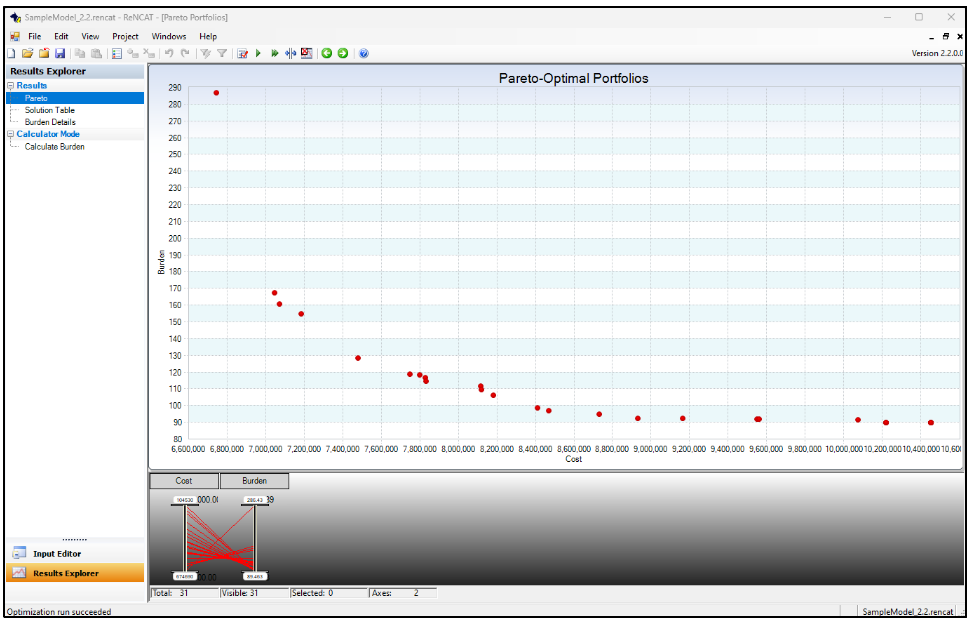

Figure 5-1. Example Pareto of Investment Portfolios

The *Pareto* screen is a good way to visualize tradeoffs between cost and burden. The shape of the Pareto front can give insights into notable tradeoff features. Regions with a steep slope represent cost points where relatively small increases in expenditures result in large reductions in burden, while regions with a shallow slope occur when additional expenditures result in smaller burden reductions. It is common to see "elbows", regions where the slope quickly changes from steep to shallow, which identifies points of diminishing returns. Gaps are also common and tend to identify particularly expensive investments that must be made to reduce burden below the pre-gap value.

5.2. Solution Table

The *Solution Table* screen displays information about each Pareto-optimal portfolio. There is one row in the solution table for each dot in the Pareto screen. The solution table shows microgrid design information in its rawest form – as switch states and facility powered status. The open/closed state of each switch is displayed, as is the cost associated with the selected state. The state of each facility is displayed as a checkbox, where a checked box means the facility is operational in this portfolio.

5.3. Burden Details

The *Burden Details* screen displays details information about burden scores for each Pareto-optimal portfolio. Selecting a portfolio of interest from the left pane will display the portfolio's details in the right pane.

Data is displayed in 5 levels of detail. The headings are also shown in 5 levels, indicating how the information is organized. Expanding a level of information causes the next deeper level of information to be displayed.

- The top level is the Overall Burden
- Nested within the Overall Burden is the total burden for each service category
- Nested within each service category is a list of population blocks, with that block's per-person burden for the relevant service category, the block's attainment factor, and the block's population
- Nested within each population block is a list of facility categories that provide the relevant service, with the service level it provides
- Nested within each facility category is a list of facilities in the category that have power in the selected investment portfolio, with the per-person effort the parent population block must expend to acquire its services, and the distance from the relevant population block to the facility

5.4. Calculate Burden

Despite its location in the *Results* screen menu, the *Calculate Burden* screen does not show results from the optimization run. Instead, it gives access to ad-hoc Social Burden calculations. It allows the burden to be calculated for any set of operational facilities. The screen displays a checkbox for each facility, where a checked box indicates the facility is operational and an unchecked box indicates it is not operational. The overall Social Burden for the selected facilities is displayed in the column's header.

You can compare different sets of operational facilities by right clicking the screen and selecting *Add New Power Scenario*. This will add a new column of checkboxes to the view. The calculated Social Burden for each column's selected facilities is displayed in the column header.

6. Modeling Topics

Some modeling decisions merit additional discussion. The following sections provide additional insight into how values for certain input screens are obtained or determined for use in a ReNCAT model.

6.1. Services as a Measure of Resilience

Some power system planning efforts focus on resilience in terms of serving pre-selected critical infrastructure loads during disruptive events. ReNCAT takes a different approach, measuring resilience in terms of access to critical services. This approach is based on research in the social justice domain[1,2,3], which asserts that well-being is best measured by people's ability to meet their needs. There is a causative chain that links the power system to the ability to meet a community's needs: power enables facilities to provide services, and access to services allows people to meet their needs.

ReNCAT captures the relationship between facilities and critical services using a sector-to-service map (see section 3.3.2, *Service Mapping*). This map indicates how well each facility category provides each type of service. Values are obtained by working with community stakeholders and representatives from the study area. These stakeholders typically determine which services are critical to residents within their community, which infrastructure assets provide those services, and the mapping and levels between infrastructure and services. This determination is done in partnership with the analyst developing the ReNCAT model. An example mapping is shown in Figure 6-1 below.

	Communications	Finance	Food	Fuel	Medical Service	Medications	Safety	Security	Shelter	Water
Bank Branch		4								
Cell Tower	4						2	2		
Gas Station			1	4						1
Grocery Store Large			5			1				2
Grocery Store Small			3			1				1
Hospital					5	2				
Hotels									3	
Internet Center	4						2	2		
Medical Center					3					
Pharmacy			2							1
Unofficial Shelter			1						5	1

Figure 6-1. Example Sector-to-Service Map

The values in the service map indicate how likely a person will be able to meet a category of need by visiting a facility in a particular sector. Values are relative – a 2 is twice as effective as a 1. Values may reflect multiple factors, such as the capacity of the facility or the expected duration of current supplies. In the optimization, greater levels of service lead to lower levels of burden; the sector-to-

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[1] Nussbaum, *Capabilities as fundamental entitlements: Sen and social justice*, https://www.tandfonline.com/doi/abs/10.1080/1354570022000077926, 2003

[2] Sen, *Human Rights and Capabilities,* https://www.tandfonline.com/doi/abs/10.1080/14649880500120491, 2005

[3] Day, R., Walker, G., Simocck, N. *Conceptualising energy use and energy poverty using a capabilities framework*, Energy Policy, 2016

service map indicates how strongly the presence of a particular type of facility impacts the Social Burden score, and for which services.

6.2. Social Burden

The Social Burden metric is a way of quantifying the time, effort, and hardship experienced when attaining needed services. It encapsulates the availability of services, the proximity of services to people, and how efforts to acquire goods and services impact individuals.

The Social Burden calculation can be roughly described as e*ffort divided by ability*. Effort captures the activities that must be carried out to access services. Ability reflects the variation in people's ability to shoulder additional hardship in the pursuit of services.

The Social Burden score is derived from two sets of information: data about facilities, and data about people. Data about facilities includes information about the type and location of facilities, the services they provide, and whether each facility is currently operational. Data about people includes the distribution of people across the study area, and people's relative ability to absorb increases in cost, time, and disruptions. These data are included in the model as outlined in sections 3.2.1. *Facilities* and 3.4. *Population Blocks*, respectively.

The Social Burden metric is defined in a way that allows equity considerations to be included in the calculation. Two people completing otherwise similar tasks may experience different levels of burden due to a variety of factors, such as financial conditions, social support structures, and mobility limitations. These differences can play a significant role in discussions of equity. To capture these factors, each population block is assigned an Attainment Factor which represents the block's relative capacity to acquire services (see section 3.4.1.2, *Attainment Factors*). A higher Attainment Factor leads to a lower burden. Fully quantifying this value can be difficult; the block's median income is often used as a proxy.

For a given ReNCAT model, the sole factor that causes two investment portfolios to have different Social Burden scores is the set of facilities that are operational. All other data is the same for every investment portfolio configuration.

6.3. Switches

In a ReNCAT model, switches represent potential microgrid boundaries. This definition of a switch usually does not match one-to-one with physical switches in the existing real-world power system. Some physical switches will need to be represented in ReNCAT while others will not. The decision to include a switch in the ReNCAT model should be based on whether the optimization should consider placing a microgrid boundary at the switch's location.

It may also be useful to add switches to the ReNCAT model at locations where there is no existing real-world switch. These "virtual" switches represent locations to evaluate the addition of a new switch as a potential microgrid boundary.

Each switch has two costs, one for its open state and one for its closed state. Costs represent both physical installation costs and operational costs at the time of power disruption. Appropriate values for these costs are highly dependent on what the switch represents.

- An existing automated SCADA-controlled switch will have zero cost for both open and closed states, as there are no additional installation costs and there is zero cost to change switch states.

- A manual switch will incur a cost to upgrade to an automatic switch if its selected switch state does not match its normal state (i.e., ReNCAT chooses to open a normally closed switch). Leaving the switch in its normal state would not incur a cost.
- A manual switch that is not upgraded incurs a cost representing the operational cost to manually change the state of the switch. Leaving the switch in its normal state would not incur a cost.
- If a switch represents a new switch location, then the cost to open the switch represents the purchase and installation cost. Leaving the switch closed is the same as not installing it and does not incur a cost.
- Creative use of switches can also represent other potential changes to grid topology, such as the potential construction of a new power line. When this type of "switch" is closed it represents adding a new power line that enables power to flow between two existing power lines in the distribution topology. When the switch is open it represents choosing not to construct the new power line. When modeled in this manner, the cost to close the switch should reflect the cost of power line construction and integration, while the cost to open the switch would be zero.

Avoid including too many switches in the model. Additional switches cause an exponential increase in the number of potential investment portfolio layouts the optimization algorithm must consider. If a real-world switch doesn't significantly change the footprint and facilities that would be included in a microgrid, consider leaving out the switch.

Just as there is not a one-to-one mapping between ReNCAT switches and real-world switches, there is not a one-to-one mapping between ReNCAT power lines and real-world conductors. A ReNCAT power line usually aggregates many individual conductors in the real-world data. ReNCAT power lines are generally bounded by switches, so leaving a real-world switch out of a ReNCAT model typically reduces the number of power line sections in the ReNCAT model as well.

6.4. Load Shedding

ReNCAT models conditions during disruptive events that prevent electrical loads from being served from their normal power sources. In most cases it is cost prohibitive to serve all normal loads from backup power sources. Instead, some loads are left unserved, a condition known as load shedding.

There are three types of load shedding in ReNCAT:

- Unpowered network segments
- Disconnected non-facility loads
- Disconnected facilities

An unpowered network segment is any power line that is not part of a microgrid and is not directly attached to a power source. All facility- and non-facility loads associated with these power lines are left unserved. There are no monetary costs associated with leaving network segments without power, other than the cost of opening switches to isolate unpowered portions of the network from microgrids.

A power line's non-facility load represents the aggregate load normally served by the line, other than loads imposed by facilities. Examples of non-facility loads include residences, business that are not represented as service-providing facilities, and any other loads not otherwise represented. Disconnecting a line's non-facility load leaves these loads unserved. Disconnecting non-facility loads has no impact on Social Burden because non-facility loads do not impact facilities' ability to provide their services. Disconnecting non-facility loads incurs a cost that represents the cost to isolate the line's non-facility loads from the rest of the microgrid.

Disconnecting a facility leaves the facility without power, unable to provide any of its services. Only facilities associated with power lines that are part of a powered microgrid are ever disconnected. Disconnecting a facility incurs a cost that represents the cost to isolate the facility from the rest of the microgrid, such as installing a switch. Disconnecting a facility causes an increase in Social Burden due to the reduced availability of services.

All three types of load shedding are done as cost saving measures. ReNCAT only sheds a load when doing so is less expensive than purchasing the additional power generation capacity needed to support the load. Furthermore, facility loads are only disconnected when doing so does not conflict with the microgrid design parameters ReNCAT is currently exploring.

The cost to disconnect a facility or non-facility load is provided by the analyst, and should be based on the cost to isolate the disconnected load from its power line. For a facility, the disconnect cost may represent the cost to install and activate a switch. For a non-facility load, it may represent the cost of multiple switches, such as a switch per region for multiple residential regions served by the power line section or multiple switches for each commercial building on the power line. It is rarely feasible to determine exactly what distribution network modifications would be necessary to disconnect a load, so applying heuristics to estimate disconnection costs may be necessary.

7. The Stand-Alone Social Burden Calculator

ReNCAT includes a stand-alone command line application that can be used to calculate Social Burden for any set of operational facilities. The application reads input data from a JSON file provided by the analyst and generates an output JSON file with Social Burden calculation details. The input JSON file format is documented in the file named `BurdenCL-input-schema.json` found in the ReNCAT installation folder.

The Social Burden calculation does not require any knowledge of the power grid; it needs to know which facilities are operational but does not need to know how facilities receive power. The input file format reflects this, requiring information about facility locations, categories, and service offerings, as well as population blocks, but does not require information about power lines, switches, or power sources.

The stand-alone Social Burden calculator is called BurdenCl.exe, and is found in the ReNCAT installation folder. To run the stand-alone calculator, first prepare an input JSON file and then execute the following command at a command prompt:

```
BurdenCL <input> <output>
```

where *<input>* is the name of the input JSON file and *<output>* is the name of the desired output file. If an output file is not specified, it will write the output to stdout (the console). If an input file is not specified, it will read input from stdin.

Results include the overall Social Burden for the set of facilities identified in the input; the per-service Social Burden for each service category; and for each population block, the per-person total Social Burden and the block's per-service Social Burden for each service category. Analysis of this information can yield valuable insights into how burden varies across the study region from both an aggregate and a per-service perspective.

8. Tutorial

The following tutorial will walk you through building and running a simple ReNCAT model. Data for this model is located in Appendix A. The data used in this sample model is notional and should not be used as input data for developing ReNCAT models for other communities or applications.

To start a new model in ReNCAT, click the white "new" icon on the top left or go to File→New. Save your model as "SampleModel." If you are copying data from a spreadsheet into the data grids in ReNCAT, go to the correct grid and right click and select "Insert Copied Cells." You can also enter the data manually, but it's recommended to organize all data in a spreadsheet for maintainability and then copy and paste the data into the model. Screenshots and model results were generated using ReNCAT Version 2.2.0.0.

8.1. Power Infrastructure

Step 1: Enter data for the power lines in the "Power Line" data grid. This sample model will contain data for power lines and their noncritical loads. All noncritical loads should be marked as disconnect eligible and have an associated cost to disconnect. To complete this data grid:

- Copy and paste in the power lines, associated non-critical loads, and disconnect costs
- Check the "Is Disconnect Eligible (Y/N)" box for all lines

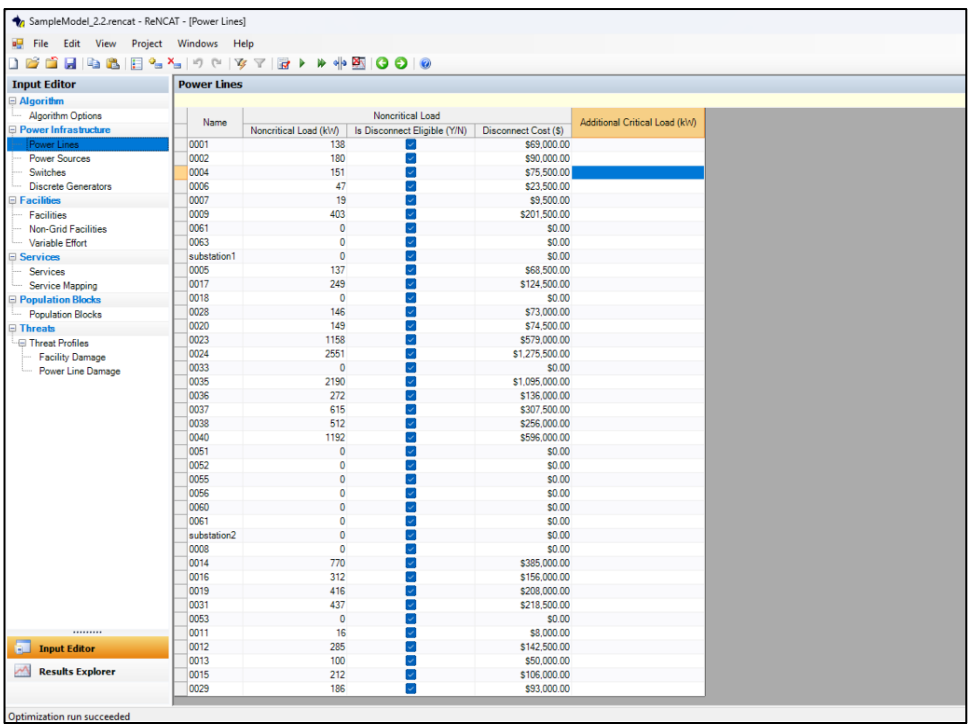


Figure 8-1. Power Line Inputs for Sample Model

These power lines represent each segment of a line that the optimization will choose to energize or leave unpowered. While the lines can be named anything, they are labeled here by their sub circuit. As a reminder, critical loads are specified for each facility in another grid.

Step 2: After power lines have been added, the next step is to add power sources in the "Power Sources" data grid. These are any exiting power sources (such as backup generators) that can be used during a grid outage. We are assuming there are no existing power sources in this area. Leave this data grid blank.

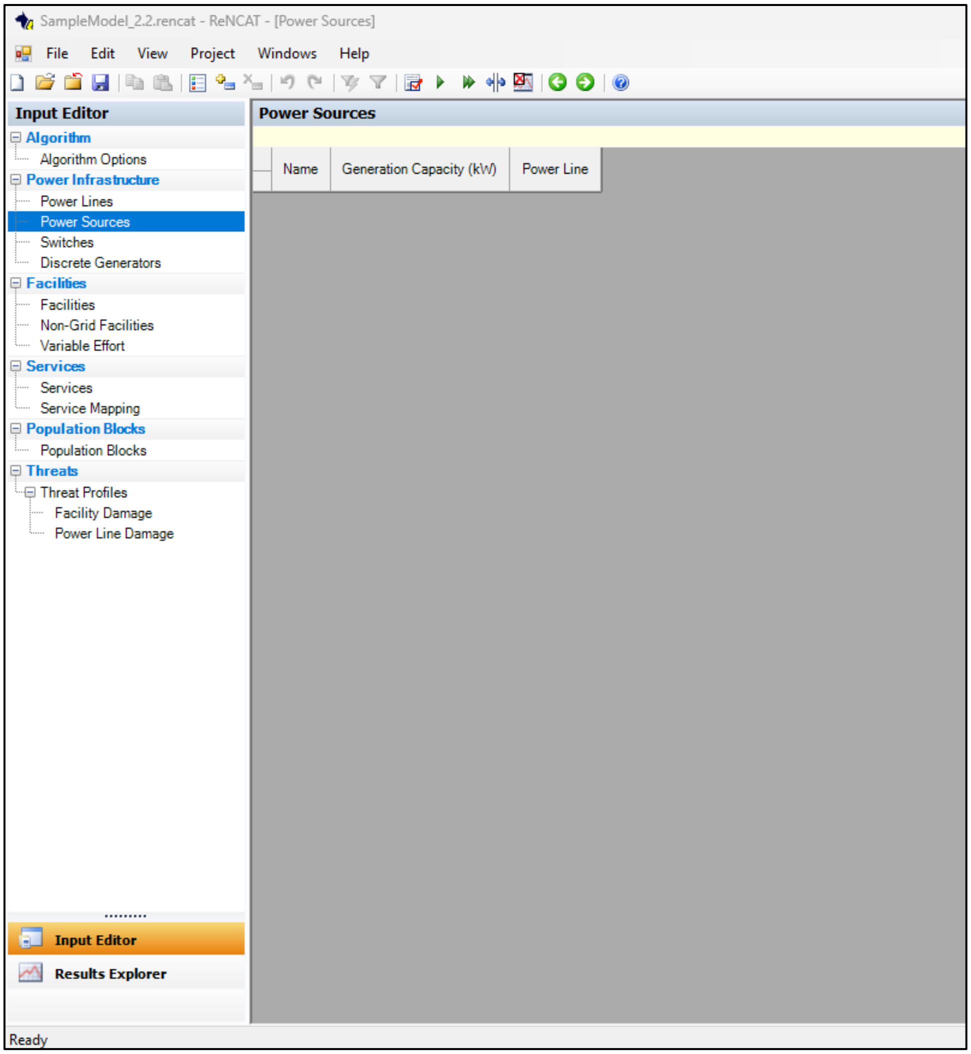
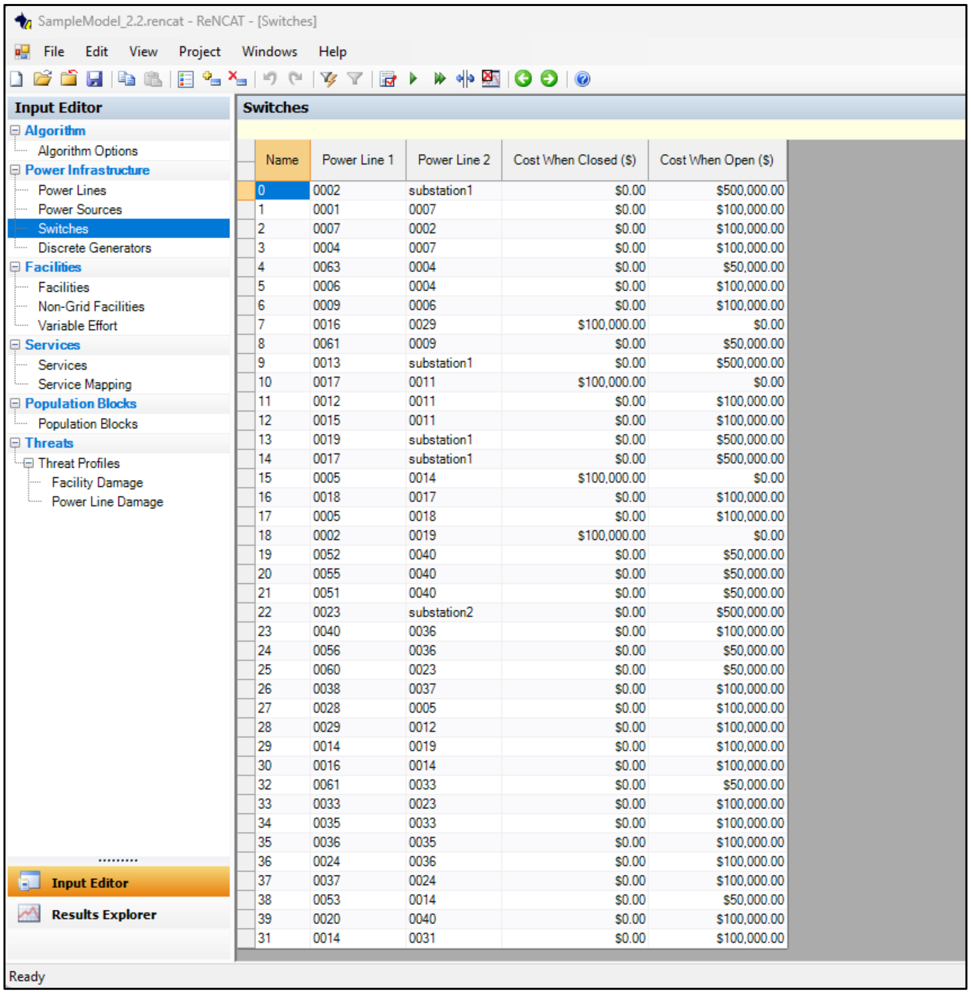


Figure 8-2. Power Source Inputs for Sample Model

Step 3: Next we'll add the data for switches. In ReNCAT, switches must be located between two power line segments. Switches allow power lines to either be powered or not powered. To complete this data grid:

- Navigate to the "Switches" data grid
- Copy and paste in the switch names and their associated power lines, cost when closed, and cost when opened

Each switch must define two power lines which indicate the two power lines between which the switch is located. There may be associated costs with opening or closing the switch depending on its normal configuration and/or whether it already exists. For more information on determining switch costs, see *Section 3.1.3: Switches*.



Name	Power Line 1	Power Line 2	Cost When Closed ($)	Cost When Open ($)
0	0002	substation1	$0.00	$500,000.00
1	0001	0007	$0.00	$100,000.00
2	0007	0002	$0.00	$100,000.00
3	0004	0007	$0.00	$100,000.00
4	0063	0004	$0.00	$50,000.00
5	0006	0004	$0.00	$100,000.00
6	0009	0006	$0.00	$100,000.00
7	0016	0029	$100,000.00	$0.00
8	0061	0009	$0.00	$50,000.00
9	0013	substation1	$0.00	$500,000.00
10	0017	0011	$100,000.00	$0.00
11	0012	0011	$0.00	$100,000.00
12	0015	0011	$0.00	$100,000.00
13	0019	substation1	$0.00	$500,000.00
14	0017	substation1	$0.00	$500,000.00
15	0005	0014	$100,000.00	$0.00
16	0018	0017	$0.00	$100,000.00
17	0005	0018	$0.00	$100,000.00
18	0002	0019	$100,000.00	$0.00
19	0052	0040	$0.00	$50,000.00
20	0055	0040	$0.00	$50,000.00
21	0051	0040	$0.00	$50,000.00
22	0023	substation2	$0.00	$500,000.00
23	0040	0036	$0.00	$100,000.00
24	0056	0036	$0.00	$50,000.00
25	0060	0023	$0.00	$50,000.00
26	0038	0037	$0.00	$100,000.00
27	0028	0005	$0.00	$100,000.00
28	0029	0012	$0.00	$100,000.00
29	0014	0019	$0.00	$100,000.00
30	0016	0014	$0.00	$100,000.00
32	0061	0033	$0.00	$50,000.00
33	0033	0023	$0.00	$100,000.00
34	0035	0033	$0.00	$100,000.00
35	0036	0035	$0.00	$100,000.00
36	0024	0036	$0.00	$100,000.00
37	0037	0024	$0.00	$100,000.00
38	0053	0014	$0.00	$50,000.00
39	0020	0040	$0.00	$100,000.00
31	0014	0031	$0.00	$100,000.00

Figure 8-3. Switch Inputs for Sample Model

Step 4: Define discrete generation options. These are generator options that can be purchased to power segments of the distribution system based on critical and noncritical load. These can represent diesel, natural gas, propane, etc. generators that are sold in discrete sizes or can represent units of a PV system. ReNCAT will round up to an integer quantity of generators or PV units to power microgrids since generators cannot be purchased in fractional units. To complete this data grid:

- Navigate to the "Discrete Generators" data grid
- Copy and paste in the five discrete generator options, their capacity, and their cost

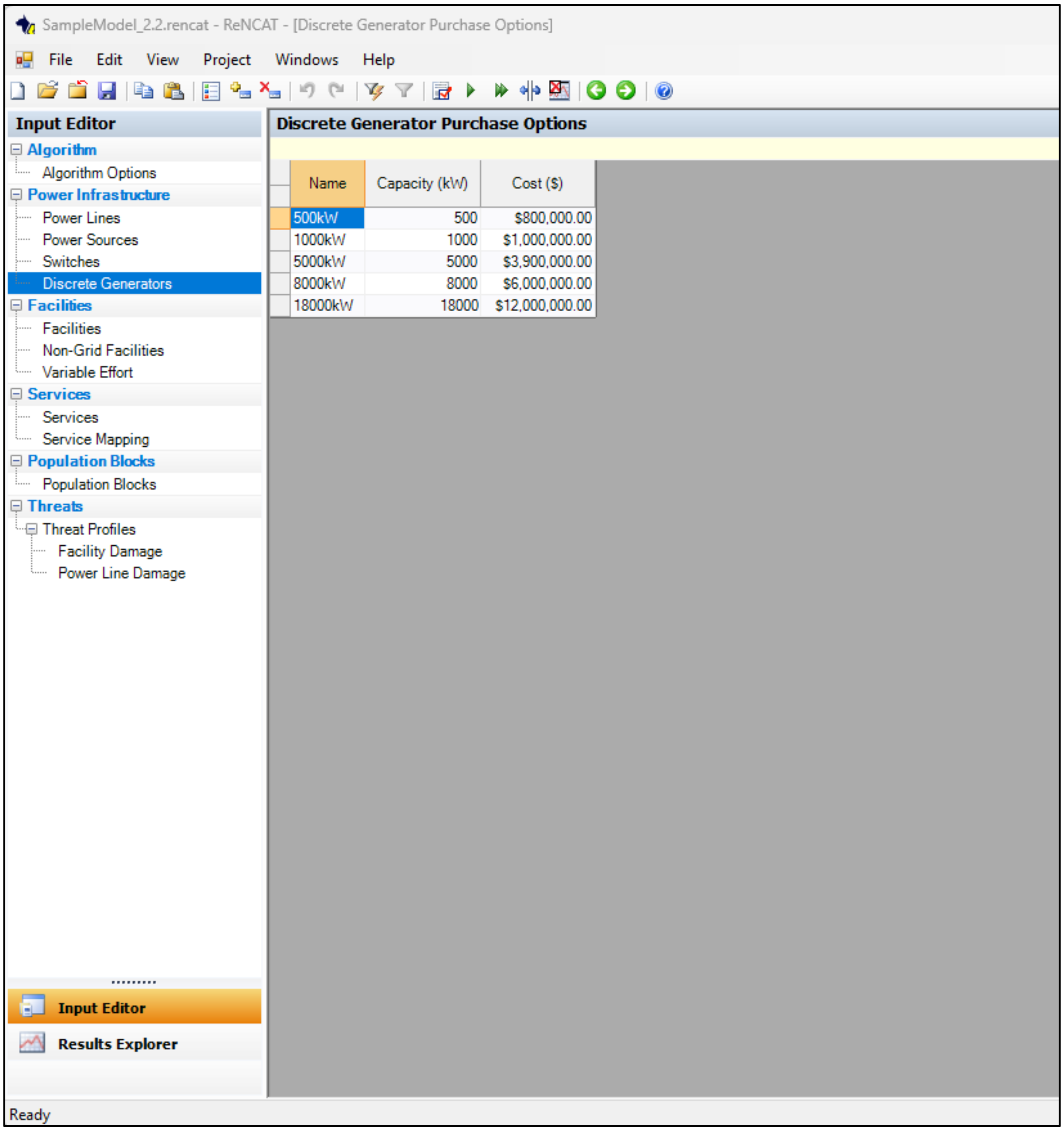


Figure 8-4. Discrete Generator Inputs for Sample Model

8.2. Facilities

The facilities data grids in ReNCAT represent critical facilities and their associated characteristics. They also define threat profiles for use by the optimization and allow the user to make granular changes to the effort parameter of Social Burden.

Step 1: Add facilities. The facilities data grid designates the sectors that are included in the analysis as well as the individual buildings/assets. To complete this data grid:

- Navigate to the “Facilities” data grid
- In the “Facility Categories” grid on the left, add a row for each sector with the sector name

- For each sector type, click on the sector name and copy and paste all facilities associated with that sector into the right "Facilities" grid. Each facility will have a name, associated powerline, geographic coordinates, disconnect cost, load, and effort parameters.
- Check the "Is Disconnect Eligible (Y/N)?" box for all facilities to indicate that the critical load can be disconnected. Any disconnected loads will incur the disconnect cost.

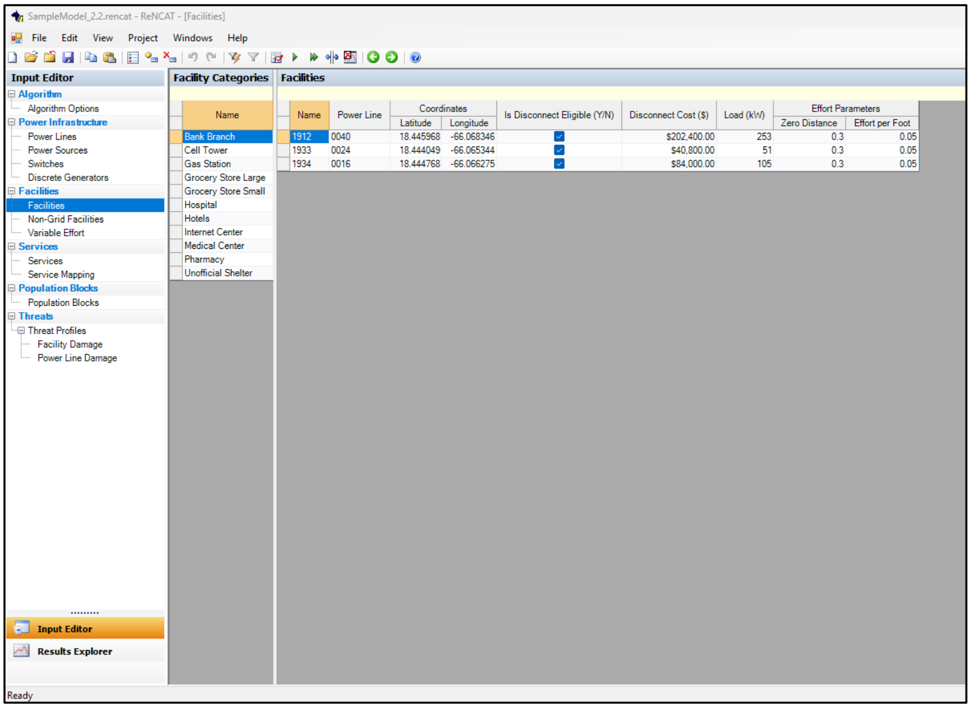


Figure 8-5. Facility Inputs for Sample Model

Step 2: Define Non-Grid Facilities. Non-grid facilities are infrastructure assets that provide critical services but do not rely on power from the grid to operate. In our small sample model, we do not have any on-grid facilities, so leave this data grid blank.

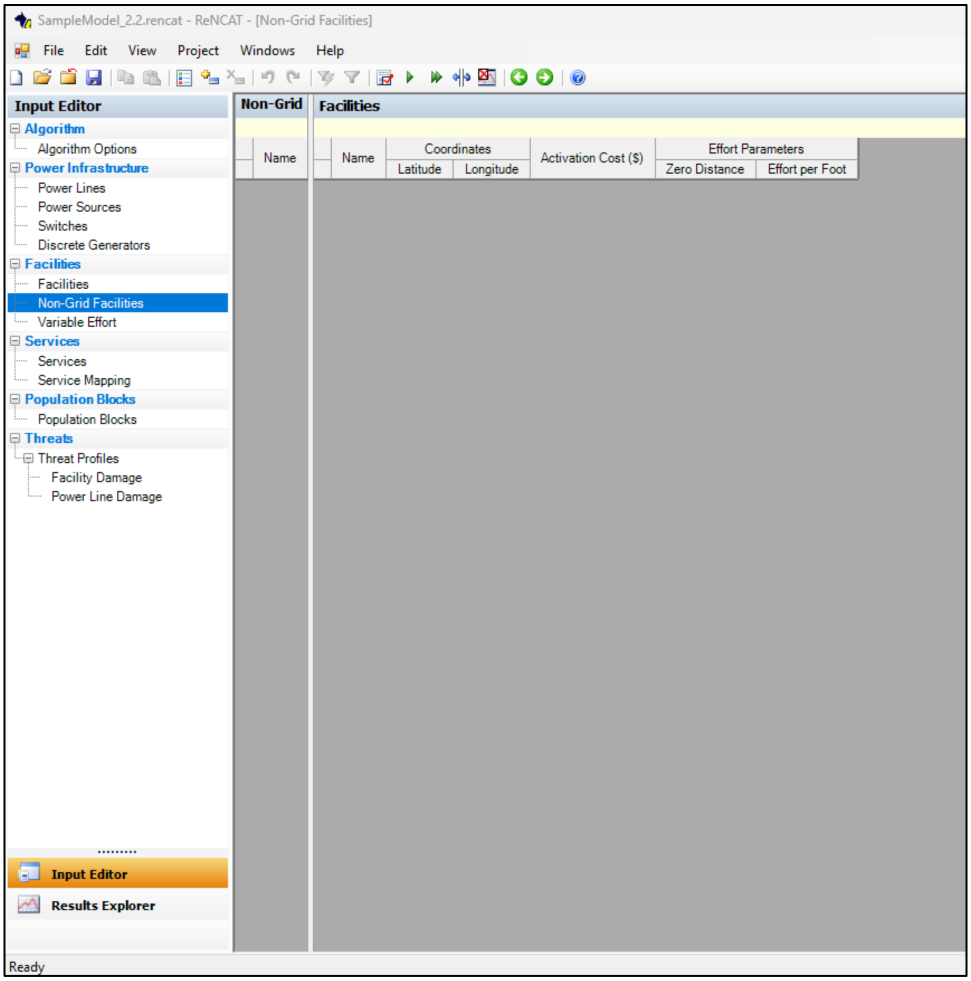


Figure 8-6. Non-Grid Facility Inputs for Sample Model

Step 3: Define variable effort. The "Variable Effort" data grid is used to specify the effort needed to access services at a given facility when there are a specific number of facilities in a sector that are powered. These parameters are only used when the number of powered facilities is equal to the count specified. The sample model does not use variable effort, so leave this data grid blank.

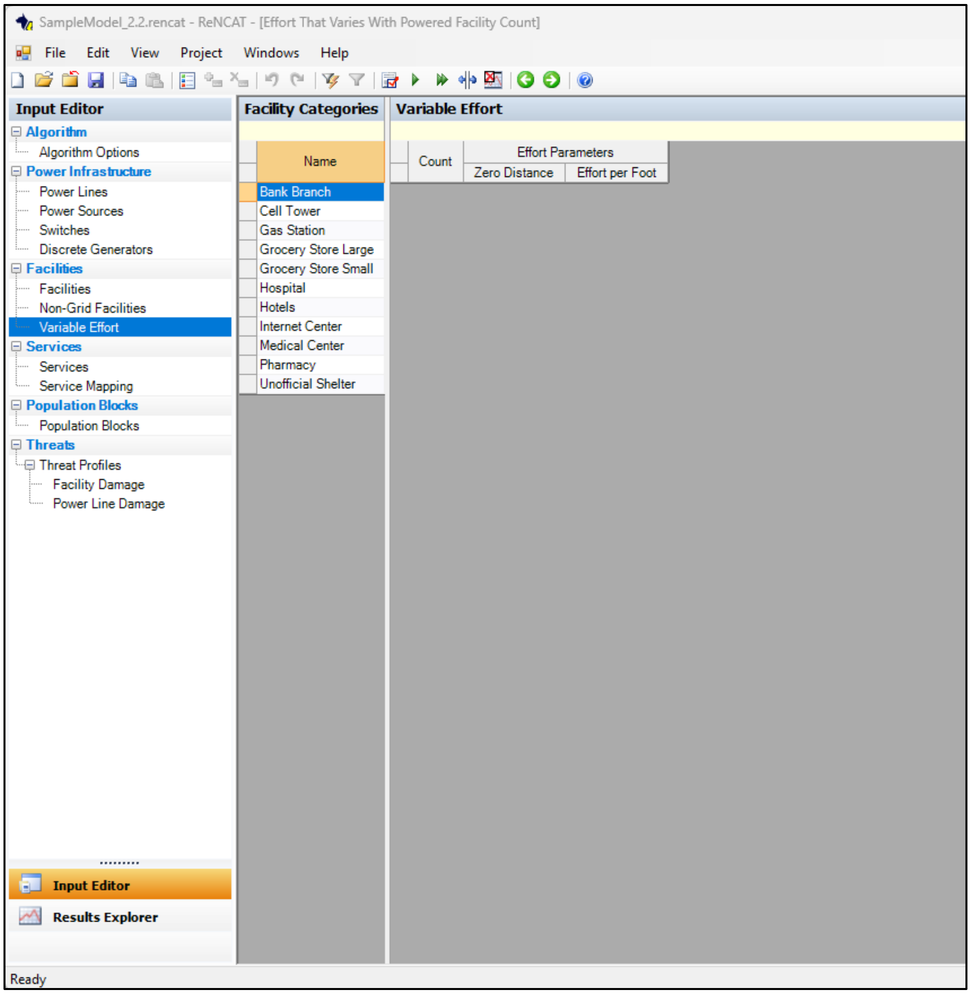


Figure 8-7. Variable Effort Inputs for Sample Model

8.3. Services

The services grids define the types of critical services that are provided by critical facilities and the levels at which they are provided.

Step 1: Define service types. The services grid designates the services that are included in the analysis. Services represent critical services that the community wants to keep online during the event of a grid outage. To complete this data grid:

- Navigate to the "Services" data grid
- Copy and paste the list of services
- Leave the "weight" field blank. This is used to scale burden and defaults to 1 if left blank.

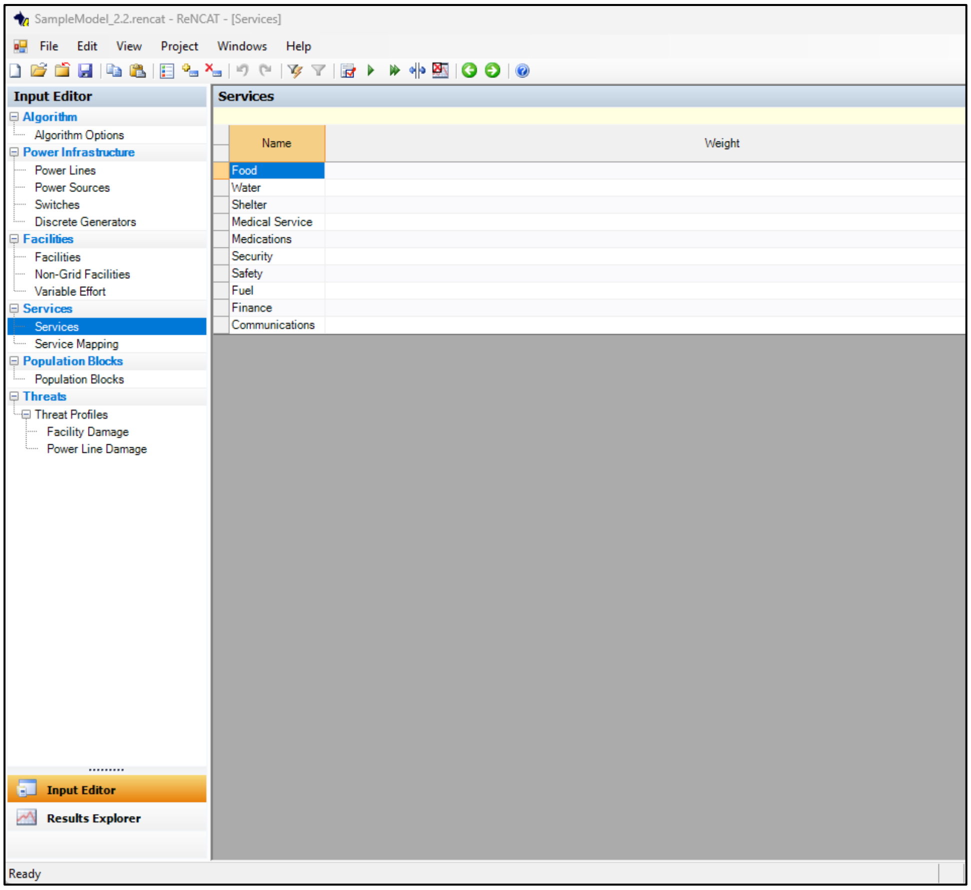
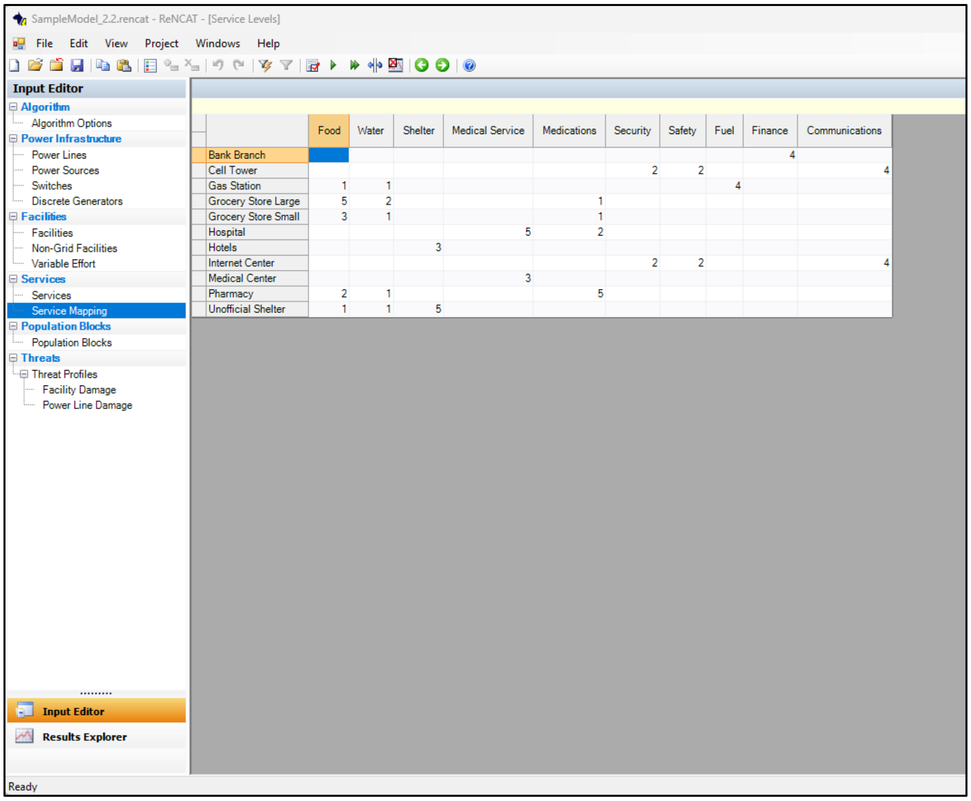


Figure 8-8. Service Inputs for Sample Model

Step 2: Define the sector to service mapping. The service mapping grid defines how sectors are mapped to services. All sectors defined in the "Facilities" grid will appear as row labels and all services defined in the "Services" grid will appear as column labels. Service levels indicate how much of a given service can be provided by a given sector. To complete this data grid:

- Navigate to the "Service Mapping" data grid
- Enter the service levels by selecting the correct category in the table. Levels range from 1 (very low) to 5 (very high).



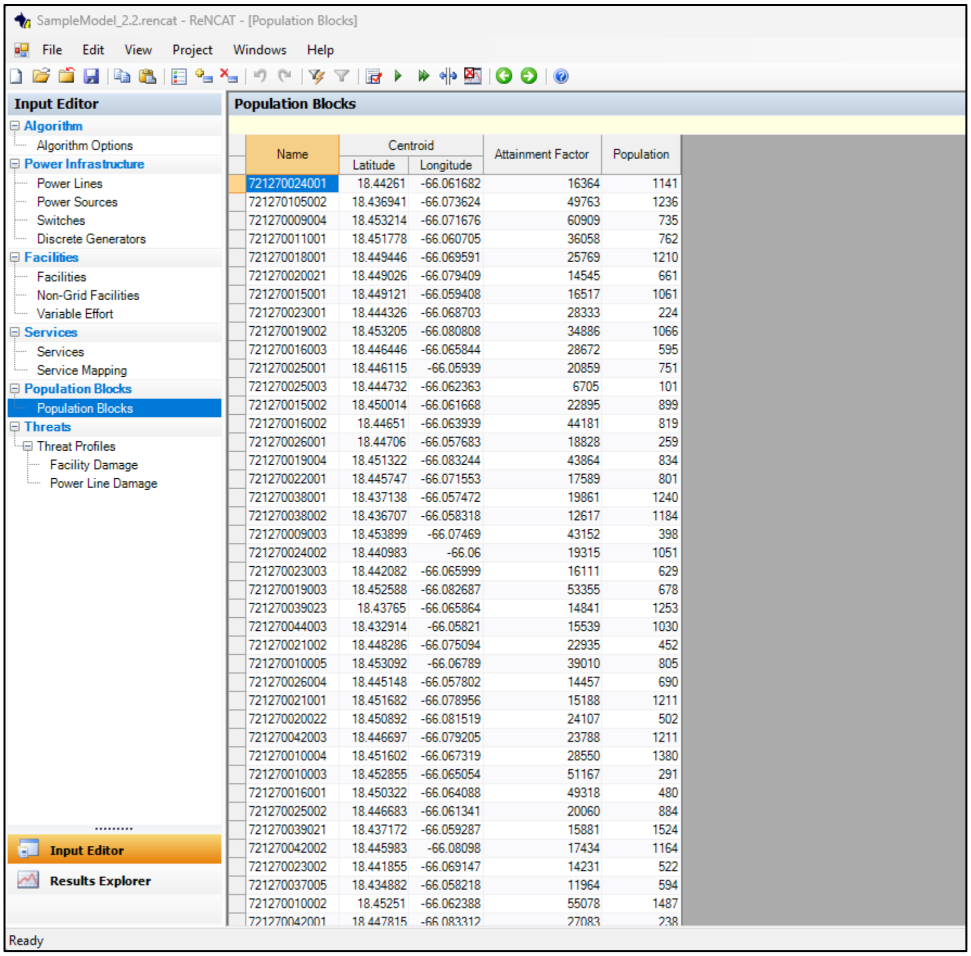
	Food	Water	Shelter	Medical Service	Medications	Security	Safety	Fuel	Finance	Communications
Bank Branch									4	
Cell Tower						2	2			4
Gas Station	1	1						4		
Grocery Store Large	5	2			1					
Grocery Store Small	3	1			1					
Hospital				5	2					
Hotels			3							
Internet Center						2	2			4
Medical Center				3						
Pharmacy	2	1			5					
Unofficial Shelter	1	1	5							

Figure 8-9. Service Mapping Inputs for Sample Model

8.4. Population Blocks

The last data grid represents the population block level data that ReNCAT uses to calculate Social Burden. This sample model uses census block groups as the population blocks and household median income as the attainment factor. Population blocks are needed for the geographical area being analyzed. To complete this data grid:

- Navigate to the "Population Blocks" data grid
- Copy and paste in the census block group data including the location, household median income, and population for each census block group



Name	Centroid		Attainment Factor	Population
	Latitude	Longitude		
721270024001	18.44261	-66.061682	16364	1141
721270105002	18.436941	-66.073624	49763	1236
721270009004	18.453214	-66.071676	60909	735
721270011001	18.451778	-66.060705	36058	762
721270018001	18.449446	-66.069591	25769	1210
721270020021	18.449026	-66.079409	14545	661
721270015001	18.449121	-66.059408	16517	1061
721270023001	18.444326	-66.068703	28333	224
721270019002	18.453205	-66.080808	34886	1066
721270016003	18.446446	-66.065844	28672	595
721270025001	18.446115	-66.05939	20859	751
721270025003	18.444732	-66.062363	6705	101
721270015002	18.450014	-66.061668	22895	899
721270016002	18.44651	-66.063939	44181	819
721270026001	18.44706	-66.057683	18828	259
721270019004	18.451322	-66.083244	43864	834
721270022001	18.445747	-66.071553	17589	801
721270038001	18.437138	-66.057472	19861	1240
721270038002	18.436707	-66.058318	12617	1184
721270009003	18.453899	-66.07469	43152	398
721270024002	18.440983	-66.06	19315	1051
721270023003	18.442082	-66.065999	16111	629
721270019003	18.452588	-66.082687	53355	678
721270039023	18.43765	-66.065864	14841	1253
721270044003	18.432914	-66.05821	15539	1030
721270021002	18.448286	-66.075094	22935	452
721270010005	18.453092	-66.06789	39010	805
721270026004	18.445148	-66.057802	14457	690
721270021001	18.451682	-66.078956	15188	1211
721270020022	18.450892	-66.081519	24107	502
721270042003	18.446697	-66.079205	23788	1211
721270010004	18.451602	-66.067319	28550	1380
721270010003	18.452855	-66.065054	51167	291
721270016001	18.450322	-66.064088	49318	480
721270025002	18.446683	-66.061341	20060	884
721270039021	18.437172	-66.059287	15881	1524
721270042002	18.445983	-66.08098	17434	1164
721270023002	18.441855	-66.069147	14231	522
721270037005	18.434882	-66.058218	11964	594
721270010002	18.45251	-66.062388	55078	1487
721270042001	18.447815	-66.083312	27083	238

Figure 8-10. Population Block Inputs for Sample Model

8.5. Threats

Step 1: Define threat profiles. The ReNCAT model will include a default threat profile. If other threat profiles are included, they will be named and defined in the "Threat Profiles" screen. These typically represent threats or combinations of threats such as "100-year flood." In this sample model, we will use the default option. Check the box to include the default profile in the optimization.

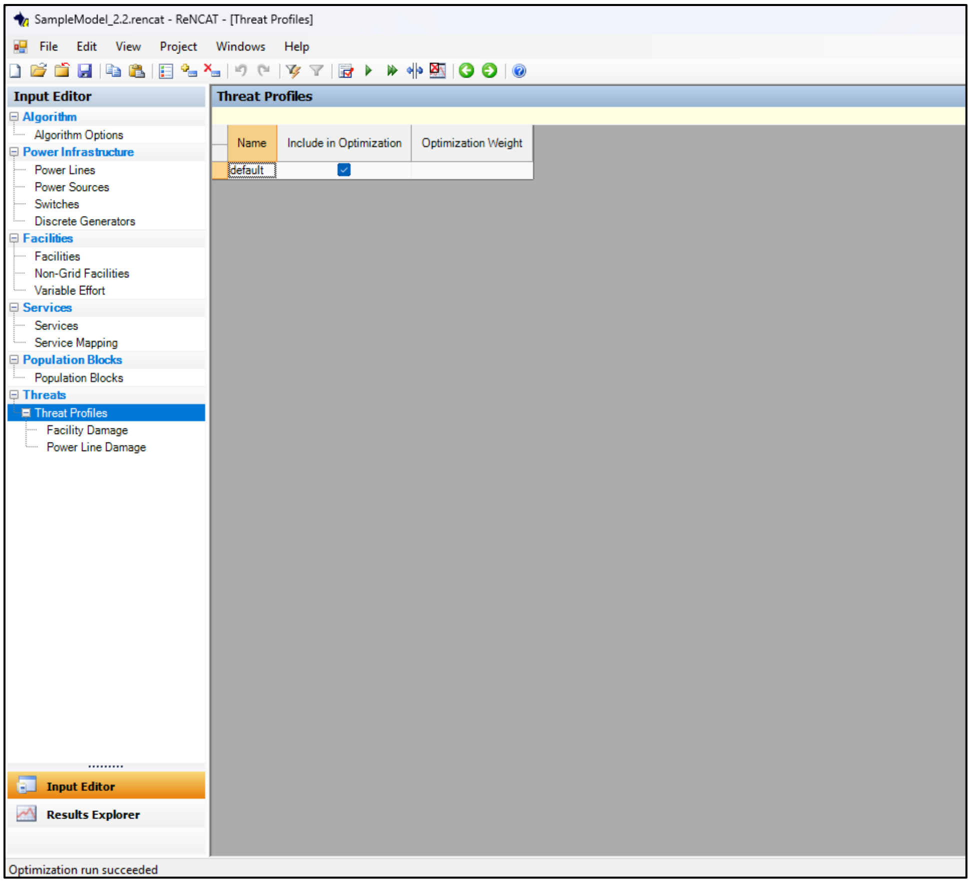


Figure 8-11. Threat Profile Inputs for Sample Model

Step 2: Specify which facilities will be damaged in each threat profile. In our sample model, no facilities are damaged in the default profile. The grid has a checkbox for each facility under each inclusion profile. Similar to the facilities data grid, click on the sector name on the left grid to see the list of facilities on the right grid. If a facility should be damaged in a given threat profile, check the box for that facility. Facilities with checked boxes will not be eligible to be powered by microgrids. To complete this data grid:

- Navigate to the "Threat Facility Damage" data grid
- For each sector, look through the list of facilities and ensure no boxes are checked (they should already be unchecked for the default threat profile)

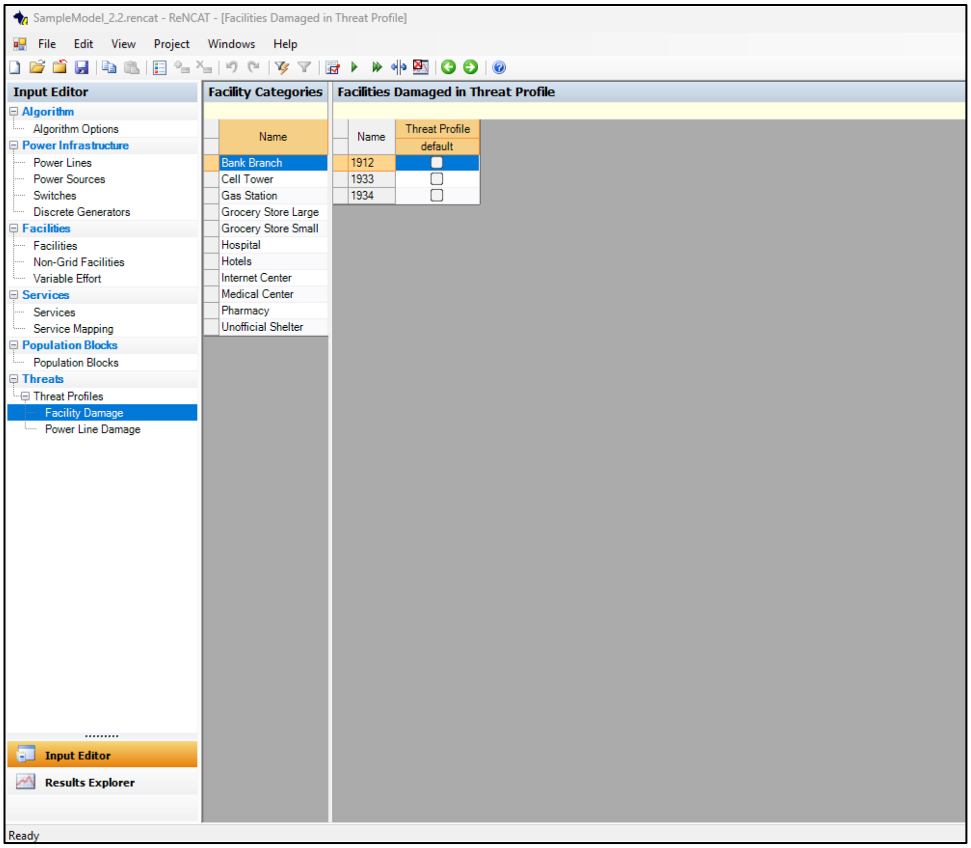


Figure 8-12. Facility Damage Inputs for Sample Model

Step 3: Define line damage. The "Threat Line Damage" data grid is used to identify which power lines are unable to carry power in each threat profile. The sample model does not use line damage, so leave this data grid blank and ensure the boxes are unchecked.

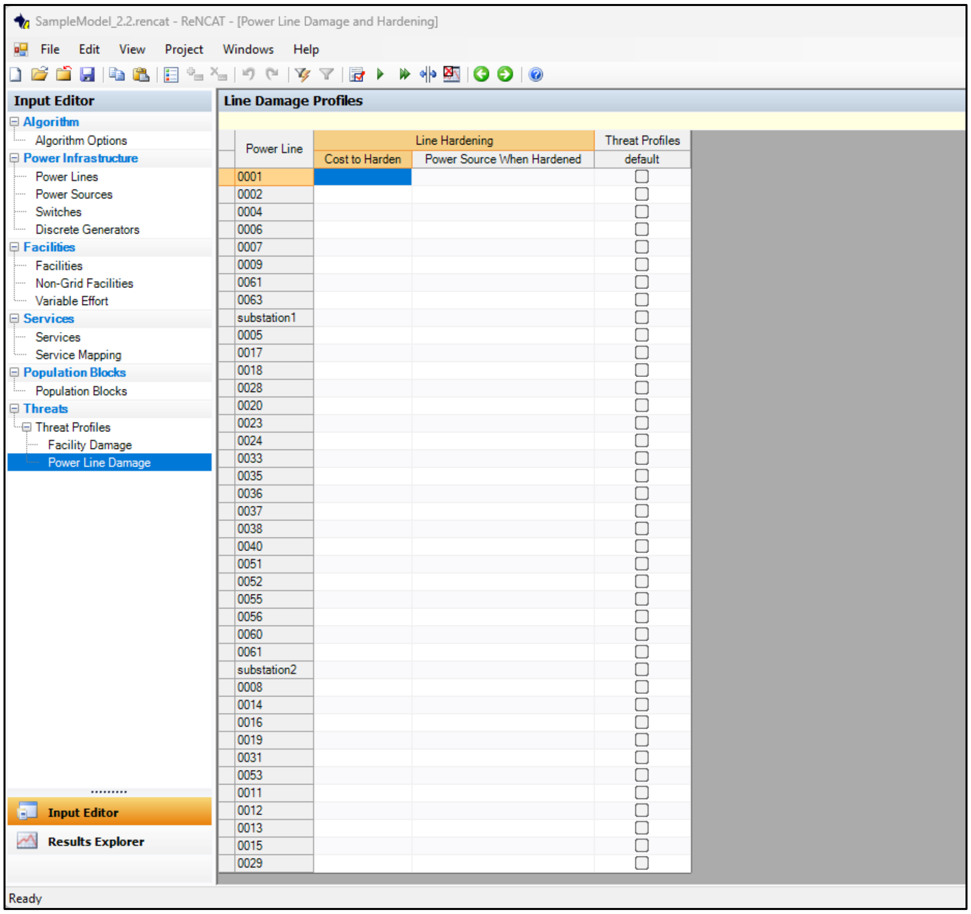


Figure 8-13. Power Line Damage Inputs for Sample Model

8.6. Running the Model

To run the model, select the desired setting under the "Algorithm Options" grid. Default values are fine for this sample model. To run the optimization, click the green arrow in the toolbar. Depending on your computer and the optimization settings, this model could take anywhere from ~40 min to ~24 hrs to run.

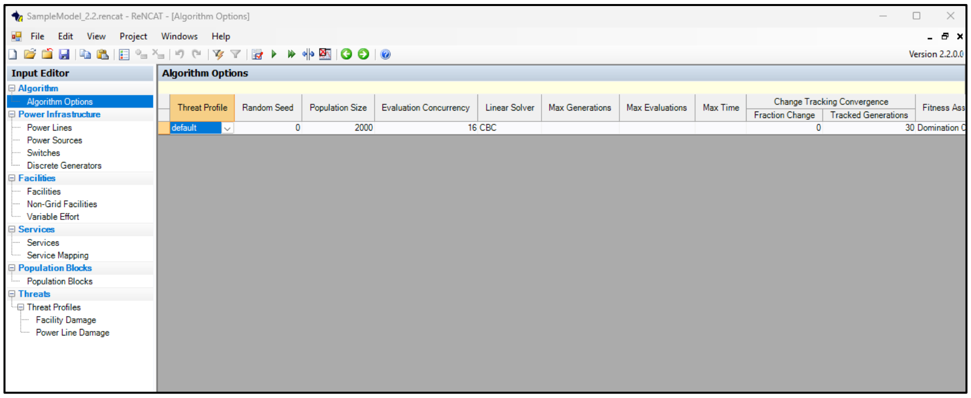


Figure 8-14. Algorithm Options for Running the Sample Model

8.7. Results

One the optimization has finished running, results can be viewed by navigating to the "Results Explorer" tab on the bottom left of the screen. There are three types of results to explore:

- The Pareto
- The Solution Table
- The Burden Details

The "Pareto" result contains a Pareto chart showing every Pareto-optimal solution found by the genetic algorithm as a function of burden and cost. Each solution (dot) represents a portfolio of one or more microgrids. Usually the "sweet spot" is where burden decreases but the cost is still relatively low (look at the 3rd portfolio from the left).

Exercise: Use the sliders at the bottom left of the screen to filter solution based on desired burden and/or cost levels.

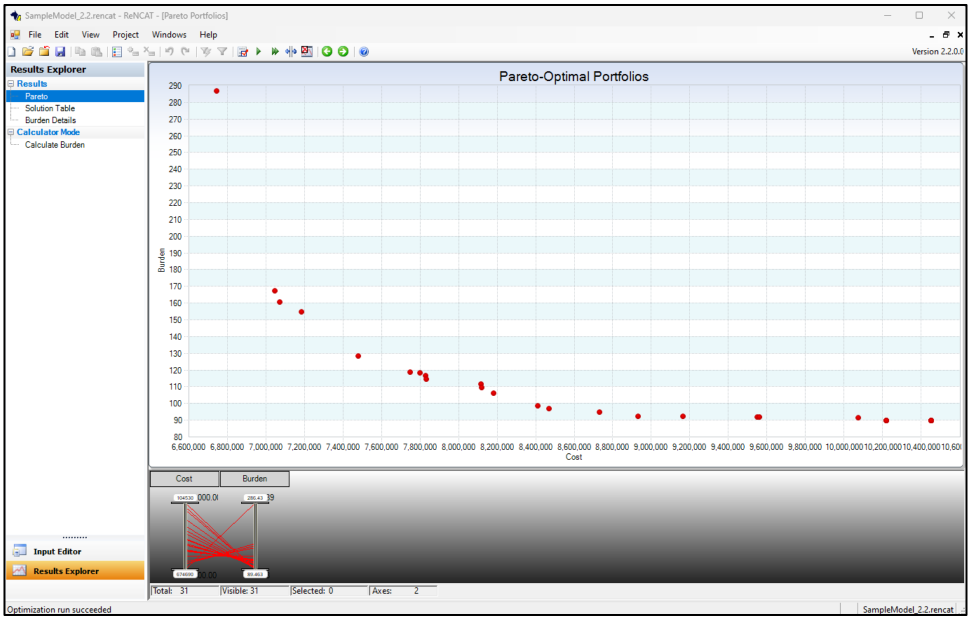


Figure 8-15. Pareto-Optimal Investment Portfolios for the Sample Model

The "Solution Table" shows the details of each portfolio (the dots from the Pareto). For each portfolio, the results include:

- Burden
- Cost
- Number of subgrids
- Position of every switch and any associated costs for that configuration
- Which facilities are included

Exercise: Look at the different solutions and compare what changes and what stays the same as the cost of the portfolios increases. Are there facilities that are always powered? Powered only in more expensive solutions? Are certain switches closed at some price points but not at others? What trends do you see across the portfolios and what is causing them?

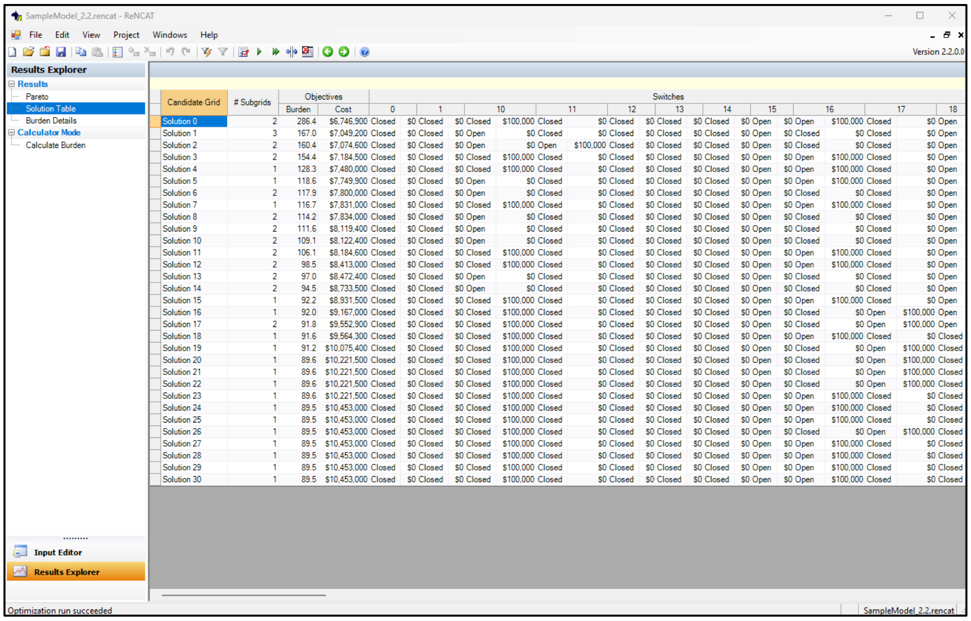


Figure 8-16. Solution Table for the Sample Model

The "Burden Details" result provides an in-depth look at Social Burden for each portfolio (solution). Burden is broken down by:

- Service category
- Population block
- Sector
- Individual facility

An overview of the structure of the results is given on the top right. Exercise: How does Social Burden at the individual service level change as the price of portfolios increases? Are there any service types that are only available at higher price points?

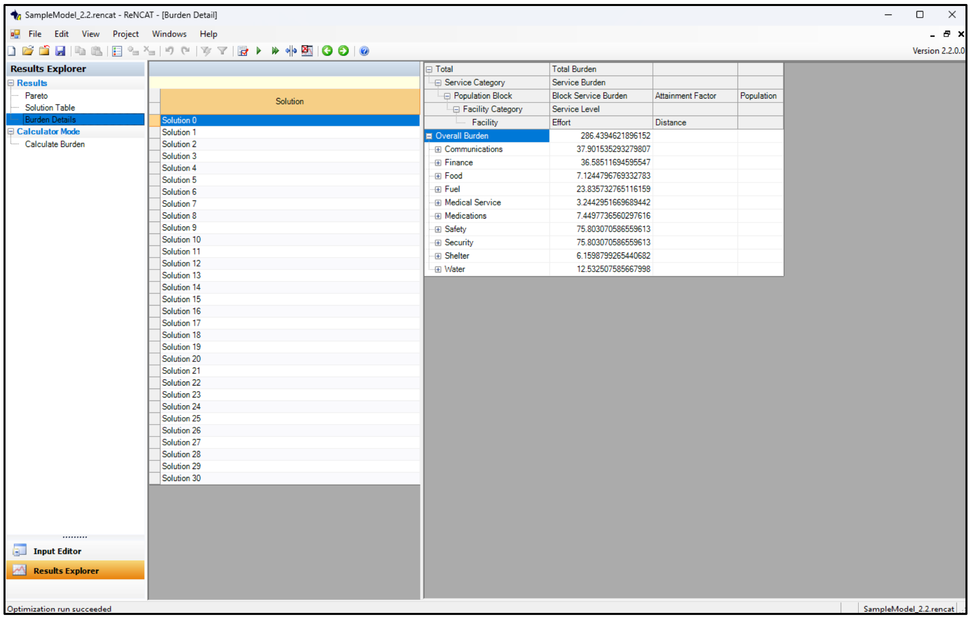


Figure 8-17. Burden Details for the Sample Model

Appendix A. Sample Model Data

This appendix contains the data used to build the sample model. Copy into a spreadsheet for use with the tutorial in Section 8: *Tutorial*.

Table 2. Power Line Data for Sample Model

Subcircuit	Noncritical Load (kW)	Disconnect Cost ($)
0001	138	69000.00
0002	180	90000.00
0004	151	75500.00
0006	47	23500.00
0007	19	9500.00
0009	403	201500.00
0061	0	0.00
0063	0	0.00
substation1	0	0.00
0005	137	68500.00
0017	249	124500.00
0018	0	0.00
0028	146	73000.00
0020	149	74500.00
0023	1158	579000.00
0024	2551	1275500.00
0033	0	0.00
0035	2190	1095000.00
0036	272	136000.00
0037	615	307500.00
0038	512	256000.00
0040	1192	596000.00
0051	0	0.00
0052	0	0.00
0055	0	0.00
0056	0	0.00
0060	0	0.00
0061	0	0.00
substation2	0	0.00
0008	0	0.00
0014	770	385000.00
0016	312	156000.00
0019	416	208000.00
0031	437	218500.00

0053	0	0.00
0011	16	8000.00
0012	285	142500.00
0013	100	50000.00
0015	212	106000.00
29	186	93000.00

Table 3. Switch Data for Sample Model

Switch ID	Power Line 1	Power Line 2	Cost When Closed ($)	Cost When Open ($)
0	0002	substation1	0	500000
1	0001	0007	0	100000
2	0007	0002	0	100000
3	0004	0007	0	100000
4	0063	0004	0	50000
5	0006	0004	0	100000
6	0009	0006	0	100000
7	0016	0029	100000	0
8	0061	0009	0	50000
9	0013	substation1	0	500000
10	0017	0011	100000	0
11	0012	0011	0	100000
12	0015	0011	0	100000
13	0019	substation1	0	500000
14	0017	substation1	0	500000
15	0005	0014	100000	0
16	0018	0017	0	100000
17	0005	0018	0	100000
18	0002	0019	100000	0
19	0052	0040	0	50000
20	0055	0040	0	50000
21	0051	0040	0	50000
22	0023	substation2	0	500000
23	0040	0036	0	100000
24	0056	0036	0	50000
25	0060	0023	0	50000
26	0038	0037	0	100000
27	0028	0005	0	100000
28	0029	0012	0	100000
29	0014	0019	0	100000
30	0016	0014	0	100000
32	0061	0033	0	50000
33	0033	0023	0	100000

34	0035	0033	0	100000
35	0036	0035	0	100000
36	0024	0036	0	100000
37	0037	0024	0	100000
38	0053	0014	0	50000
39	0020	0040	0	100000
31	0014	0031	0	100000

Table 4. Generator Data for Sample Model

Name	Capacity (kW)	Cost ($)
500kW	500	800000
1000kW	1000	1000000
5000kW	5000	3900000
8000kW	8000	6000000
1800kW	18000	12000000

Table 5. Facility Data for Sample Model

Facility Category	Facility ID	Power Line	Latitude	Longitude	Load (kW)	Disconnect Allowed	Disconnect Cost ($)
Bank Branch	1934	0016	18.444768	-66.066275	105	1	84000
Bank Branch	1933	0024	18.444049	-66.065344	51	1	40800
Bank Branch	1912	0040	18.445968	-66.068346	253	1	202400
Cell Tower	1936	0024	18.445555	-66.066111	618	1	494400
Cell Tower	2071	0037	18.442222	-66.063889	3	1	2400
Cell Tower	2072	0037	18.442444	-66.063917	26	1	20800
Gas Station	2075	0015	18.44134	-66.063984	2	1	1600
Gas Station	2078	0029	18.443199	-66.066936	5	1	4000
Gas Station	2125	0035	18.447167	-66.072637	32	1	25600
Gas Station	2132	0023	18.446905	-66.076686	113	1	90400
Gas Station	2204	0023	18.445921	-66.077651	10	1	8000
Gas Station	2347	0001	18.444866	-66.070637	2	1	1600
Grocery Store Large	2134	0023	18.447647	-66.075933	85	1	68000
Grocery Store Large	1931	0024	18.446305	-66.066957	78	1	62400
Grocery Store Small	733	0009	18.443885	-66.072745	5	1	4000
Grocery Store Small	1910	0024	18.444903	-66.067012	47	1	37600

Grocery Store Small	2135	0060	18.448888	-66.076242	18	1	14400
Hospital	1913	0051	18.444786	-66.069582	423	1	338400
Hospital	1921	0052	18.445001	-66.069248	65	1	52000
Hospital	1922	0055	18.445474	-66.06931	22	1	17600
Hospital	2137	0061	18.44602	-66.073715	14	1	11200
Hotels	2077	0012	18.443408	-66.065665	7	1	5600
Hotels	601	0037	18.442675	-66.063867	7	1	5600
Internet Center	2124	0035	18.448144	-66.071519	42	1	33600
Medical Center	734	0020	18.445703	-66.07121	47	1	37600
Medical Center	898	0061	18.45082	-66.073869	733	1	586400
Medical Center	1661	0038	18.440845	-66.061493	151	1	120800
Medical Center	1914	0053	18.444981	-66.068912	25	1	20000
Medical Center	1915	0014	18.444776	-66.068777	608	1	486400
Medical Center	1923	0040	18.445395	-66.069075	39	1	31200
Medical Center	1924	0040	18.444291	-66.069237	63	1	50400
Medical Center	1935	0024	18.445899	-66.067009	29	1	23200
Pharmacy	1911	0040	18.445131	-66.068892	12	1	9600
Pharmacy	2346	0063	18.444109	-66.072328	5	1	4000
Unofficial Shelter	732	0009	18.445708	-66.072395	3	1	2400
Unofficial Shelter	2130	0009	18.446241	-66.072916	19	1	15200
Unofficial Shelter	759	0012	18.440881	-66.066424	4	1	3200
Unofficial Shelter	760	0013	18.442149	-66.067614	5	1	4000
Unofficial Shelter	887	0019	18.44225	-66.070933	5	1	4000
Unofficial Shelter	1930	0024	18.444271	-66.064721	2	1	1600
Unofficial Shelter	1909	0031	18.445015	-66.068231	17	1	13600
Unofficial Shelter	688	0035	18.448207	-66.069798	95	1	76000
Unofficial Shelter	701	0037	18.443217	-66.064305	34	1	27200

Unofficial Shelter	2076	0037	18.443242	-66.064837	17	1	13600

Table 6. Effort Parameters for Sample Model

Sector	Zero Distance	Per Foot
Unofficial Shelter	0.3	0.05
Hotels	0.3	0.05
Gas Station	0.3	0.05
Grocery Store Large	0.01	0.01
Grocery Store Small	0.5	0.1
Pharmacy	0.3	0.05
Bank Branch	0.3	0.05
Hospital	0.2	0.01
Medical Center	0.4	0.05
Cell Tower	0.3	0.05
Internet Center	0.3	0.005

Table 7. Service Mapping for Sample Model

	Communications	Finance	Food	Fuel	Medical Service	Medications	Safety	Security	Shelter	Water
Bank Branch		4								
Cell Tower	4						2	2		
Gas Station			1	4						1
Grocery Store Large			5			1				2
Grocery Store Small			3			1				1
Hospital					5	2				
Hotels									3	
Internet Center	4						2	2		
Medical Center					3					
Pharmacy			2			5				1
Unofficial Shelter			1						5	1

Table 8. Population Block Data for Sample Model

Block Group ID	Population	Household Median Income	Centroid Latitude	Centroid Longitude
721270024001	1141	16364	18.44261	-66.061682
721270105002	1236	49763	18.436941	-66.073624
721270009004	735	60909	18.453214	-66.071676
721270011001	762	36058	18.451778	-66.060705
721270018001	1210	25769	18.449446	-66.069591
721270020021	661	14545	18.449026	-66.079409
721270015001	1061	16517	18.449121	-66.059408
721270023001	224	28333	18.444326	-66.068703
721270019002	1066	34886	18.453205	-66.080808
721270016003	595	28672	18.446446	-66.065844
721270025001	751	20859	18.446115	-66.05939
721270025003	101	6705	18.444732	-66.062363
721270015002	899	22895	18.450014	-66.061668
721270016002	819	44181	18.44651	-66.063939
721270026001	259	18828	18.44706	-66.057683
721270019004	834	43864	18.451322	-66.083244
721270022001	801	17589	18.445747	-66.071553
721270038001	1240	19861	18.437138	-66.057472
721270038002	1184	12617	18.436707	-66.058318
721270009003	398	43152	18.453899	-66.07469
721270024002	1051	19315	18.440983	-66.06
721270023003	629	16111	18.442082	-66.065999
721270019003	678	53355	18.452588	-66.082687
721270039023	1253	14841	18.43765	-66.065864
721270044003	1030	15539	18.432914	-66.05821
721270021002	452	22935	18.448286	-66.075094
721270010005	805	39010	18.453092	-66.06789
721270026004	690	14457	18.445148	-66.057802
721270021001	1211	15188	18.451682	-66.078956
721270020022	502	24107	18.450892	-66.081519
721270042003	1211	23788	18.446697	-66.079205
721270010004	1380	28550	18.451602	-66.067319
721270010003	291	51167	18.452855	-66.065054
721270016001	480	49318	18.450322	-66.064088
721270025002	884	20060	18.446683	-66.061341
721270039021	1524	15881	18.437172	-66.059287
721270042002	1164	17434	18.445983	-66.08098
721270023002	522	14231	18.441855	-66.069147
721270037005	594	11964	18.434882	-66.058218
721270010002	1487	55078	18.45251	-66.062388

721270042001	238	27083	18.447815	-66.083312
721279803001	0	0	18.441208	-66.079257
721270019001	824	59074	18.453657	-66.078885
721270022002	855	14355	18.442812	-66.071454
721270039022	1344	22917	18.441985	-66.074837
721270018002	1126	27933	18.452339	-66.074945